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Modeling Groundwater Flow at a Hydraulic Fracturing Site Near Pavillion, Wyoming

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Modeling Groundwater Flow at a Hydraulic Fracturing Site Near Pavillion, Wyoming

by

David Colombini

A Master's Thesis Submitted to the Faculty of

Montclair State University

In Partial Fulfillment of the Requirements

For the Degree of

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MODELING GROUNDWATER FLOW AT A HYDRAULIC FRACTURING SITE NEAR PAVILLION, WYOMING

A THESIS

Submitted in partial fulfillment of the requirements

For the degree of Master of Arts in Environmental Studies

by

DAVID COLOMBINI

Montclair State University

Montclair, NJ

2014

ABSTRACT

This thesis uses the GIS-conceptual model approach to create groundwater models investigating groundwater contamination near Pavillion, Wyoming. This area was part of a study by the US Environmental Protection Agency (EPA) in 2009 that claims domestic water well contamination originated from hydraulically fractured natural gas wells. Hydraulic fracturing is the process of injecting water, sand, and chemicals into gas and oil wells in order to stimulate well production. This has caused concern over groundwater contamination. The models show natural groundwater flow systems generally move from west to east, however, a recharge area near the center of the model locally disrupts that pattern. Fivemile Creek is the primary discharge zone, located towards the northern end of the model. Once gas production is included in the model, the groundwater flow systems change drastically; injection wells induce areas of high head that cause groundwater to flow away from them, while extraction wells draw groundwater towards them. This flow system alteration affects where advective groundwater transport carries dissolved methane. Groundwater flow patterns change direction in response to varying monthly extraction and injection rates, however proper well casing can mitigate these effects by isolating the flow occurring within a well from the surrounding groundwater flow systems. The resulting models support the EPA's conclusion that hydraulic fracturing was the most likely cause of water contamination in the area by showing that deep contaminants found at the EPA monitoring well can be traced back to a gas development well, while shallower contaminants could have originated from other areas that are not within the vicinity of natural gas wells. Proper casing is crucial for minimizing the disturbance and anthropogenic methane contamination of natural groundwater flow systems. The methodology of this thesis can be used to create groundwater models of any area where enough data is available to create realistic groundwater models.

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My thanks goes to Dr. Ophori, Dr. Galster, Dr. Feng, and Dr. Yu for their guidance, patience, and giving me the skills necessary to carry out this thesis. I am also grateful for the ongoing moral support from my parents.

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1.0 Introduction

Natural gas has become a topic of high interest as social concerns regarding anthropogenic greenhouse gas emissions become more and more prevalent. The US Environmental Protection Agency (EPA) states that natural gas power plants produce half the amount of carbon dioxide, a third the amount of nitrogen oxides, and one percent of the amount of sulfur oxides when compared to its coal counterpart (EPA, N.D.). Recent advances in gas exploration and hydraulic fracturing technologies have resulted in a tremendous increase in natural gas production and a corresponding decrease in the price of this fuel. As a result, it is considered by some to be a "bridge fuel" to renewable energy (Kargbo et al., 2010). However, this has led to many controversies about whether this transition is a step in lowering greenhouse gas emissions or a tactic to delay investment in renewable energy technology. Natural gas production has also acted as a source of income for many individuals who lease their land to oil and gas companies for natural gas extraction.

Hydraulic fracturing is a process involving the injection of large amounts of water, sand, and chemicals into drilled oil and gas wells in order to stimulate well production. The combination of this technique and directional drilling has allowed natural gas reserves—primarily in deep shale formations—that were once considered too costly to develop to become economically feasible and efficient. According to the U.S. Energy Information Administration's *Annual Energy Outlook 2013*, shale gas production is highly overshadowing its coalbed methane, tight-gas, and other natural gas source counterparts (Energy Information Administration, 2012). Also, the report states that production will exceed consumption due to power-plant efficiency in the industrial sector.

However, potential contamination of Underground Sources of Drinking Water (USDW) has become a major concern among stakeholders. Although the hydraulic fracturing process has been linked to other environmental issues such as methane emissions (Howarth, Santoro, & Ingraffea, 2011) and earthquakes (Foulger, et al., 2004), this thesis focuses specifically on groundwater contamination. Unlike surface water, which tends to move relatively quickly, groundwater moves through different aquifers with residence times ranging from two weeks to 10,000 years (Cech, 2010). As a result, proper management of groundwater aquifer quality is crucial, especially if it is a USDW. Determining the source of contamination can be challenging, due to the fact that methane can be naturally occurring in the soil being produced by microbes, called biogenic methane, as opposed to thermogenic methane associated with hydraulic fracturing located in deeper formations (Myers, 2012). In the Marcellus and Utica Shale formation regions in New York and Pennsylvania, isotopic analysis has been used to determine that methane contamination of drinking water originated from gas development wells rather than naturally-occurring biogenic methane (Osborn et al., 2011). The two forms of methane can usually be distinguished by a carbon-13 to CH_4 ratio, where carbon-13 is normally associated with thermogenic methane (Schoell, 1980). Groundwater models of sections of the Marcellus shale region in New York State were used to simulate contaminant pathways that could transport methane and other contaminants from fractured shale to shallow aquifers through advective transport and/or movement through fractures after simulating a well being hydraulically fractured (Myers, 2012).

One area of concern is the Catskill/Delaware Watershed supplying the majority of New York City's drinking water. Currently, New York City's drinking water is not filtered due to natural filtration effects carried out by the Catskill/Delaware watershed and watershed protection measures in New York City's watershed protection plans (EPA, 2007). In order to research the potential impacts of unconventional drilling to New York State aquifers, The New York State Assembly voted to extend the current moratorium on hydraulic fracturing in the state of New York until May of 2015 (Krudy, 2013). Although further research is required, it is also important to note that contamination pathways are site-specific; different hydrogeological factors such as geological makeup and presence of a confining unit will affect flow patterns. In other words, just because unconventional natural gas extraction contaminated groundwater in one area does not mean it will always contaminate groundwater; different areas have different hydrogeological characteristics that determine groundwater flow. Furthermore, the fracturing of the geology also alters these site-specific flow patterns, making contamination pathways difficult to generalize.

One case study of groundwater contamination that received significant attention was an EPA investigation of groundwater contamination near Pavillion, Wyoming between March of 2009 and April of 2011. The study was conducted as a result of complaints describing poor water quality from domestic drinking water wells in the area, including issues with taste and odors. A draft report of the study was released on December 14, 2011, which concluded that contaminants from hydraulic fracturing wells and disposal pits being released into the Wind River aquifer best explain the results obtained from the monitoring wells (Digiulio et al., 2011). However, certain stakeholders such as the American Petroleum Institute (API) issued a report questioning the validity of the study due to faulty well construction and transparency issues (American Petroleum Institute, 2012). In their report, one of the issues that the API cited was that the United States Geological Survey (USGS) was unable to sample the EPA's second monitoring well (MW02) during its survey between April and May of 2012 (Wright et al, 2012). As a result, this thesis will focus specifically on Monitoring Well 1 (MW01). The EPA turned the case over to the State of Wyoming to be the principle investigator of the contamination on June 20, 2013 and stated in an announcement that a final report would be released by September 30, 2014 (EPA, 2013).

In 2011, the EPA outlined 48 potential stakeholder-nominated nationwide cases in states such as North Dakota, Texas, New York, Pennsylvania, Colorado, and Wyoming to include in its overarching study of hydraulic fracturing on water resources (EPA, 2011). In its 2012 progress report, the EPA stated that five retrospective cases were chosen based on "proximity of population and drinking water supplies, evidence of impaired water quality, health and environmental concerns, and knowledge gaps that could be filled by a case study at each potential location. Sites were prioritized based on geographic and geologic diversity, population at risk, geologic and hydrologic features, characteristics of water resources, and land use" (EPA, 2012). The methodology that will be outlined in this thesis can be reproduced for each of these cases if data regarding model parameters is available.

Although Geographic Information Systems (GIS) has been integrated into groundwater modeling since 1987, the methodology has been more prevalent in surface water modeling rather than groundwater modeling (Jha et al., 2007). One purpose of this research is to integrate GIS into groundwater modeling in order to assess the accuracy of the challenged 2009 EPA study, which investigated the contamination from a mostly geochemical perspective, from a hydrogeological point of view.

In order to create an accurate groundwater model, one must specify known hydrogeological parameters in the modeling software, which is Groundwater Modeling Systems (GMS) in this thesis. The parameters applicable to this model are topography, hydrology, climate, geology, hydrogeology, and gas production history. These parameters will be more explained with more detail in section 3.

The topography of the area allows the model to assume known values of head at specific locations. Groundwater naturally flows from high head values to low head values, which can be calculated from known ground and water table elevations. However, when the water table elevation is unknown and it can be assumed that the geology in the natural system is uniform, elevation can be considered to be equal to specified head.

The hydrology of the area, which pertains to surface water such as rivers and lakes, also affects groundwater models because it acts as a groundwater discharge area, or sink. A river or lake is formed when the water table elevation is above the ground level elevation. Groundwater models are able to represent rivers and lakes as boundaries that restrict groundwater movement (also known as "no flow boundaries").

The climate of the area is partly determined by the amount of precipitation that is present, which in turn affects the amount of groundwater that is recharged per unit time. Steady-state groundwater models, which represent natural conditions that are not influenced by humans, are calibrated by altering hydraulic conductivity values to change the model's calculated inflow values to meet reported groundwater recharge rates. In other words, calibration is changing parameters within a known range until the model's calculated values are nearly equivalent to referenced reported values. This demonstrates quantitatively that the model's future calculations will reflect real-world situations.

The area's geology pertains to the specific rock formations that are present. These include the dimensions of the formations (mainly their depth or age). Different geological formations have different hydrogeological properties, which will in turn affect groundwater flow. Hydrogeology is an important parameter in groundwater models that is necessary to create a realistic simulation of groundwater flow patterns. The specific hydrogeological parameters used in the model include horizontal and vertical hydraulic conductivity (how quickly water moves through the formation horizontally and vertically, respectively), specific yield (a dimensionless value representing the volume of water released from storage from an unconfined aquifer as the water table changes), specific storage (the volume of water released from storage within the aquifer per unit head decline), and porosity (the percent of total volume that is void) (Duffield, N.D.).

The gas production within the area will alter the groundwater flow system as the water table levels fluctuate due to extraction and hydraulic fracturing (injection). This fluctuation, in turn, affects head values and thus groundwater flow. The production rates also vary over time, which also changes groundwater flow systems as opposed to natural factors that remain relatively constant (recharge can be an exception with varying precipitation values, but that is assumed to be constant in the models). Proper casings surrounding the gas wells also restrict groundwater flow interaction with wells, which will in turn affect where groundwater flows.

When all of these known parameters are put together into a model, their values define initial boundary conditions that determine the direction of groundwater flow. These initial conditions are represented by a "conceptual model". Once a code such as MODFLOW is selected and ran to calculate unknown head values, the resulting model is termed a "numerical model". The numerical model can be constructed to represent steady state conditions where groundwater does not leave the system and there are no human influences on groundwater flow (i.e., injection and extraction from wells), as well as a transient model that represents how human influence groundwater flow systems with well activity and groundwater can flow into and out of the system. Furthermore, the numerical model can then be used to simulate advective groundwater transport with a code called MODPATH that tracks groundwater containing dissolved methane moving through the groundwater system.

2.0 Objectives

The purpose of this thesis is to demonstrate how GIS data can be used to efficiently create highly-detailed groundwater models to investigate a groundwater contamination case study in Pavillion, Wyoming. Specifically, the objectives are:

1. Use GMS to simulate where contaminants located at EPA Monitoring Well 1 (MW01) could have originated from.

2. Use GIS to map the transport pathways found in objective 1 for clearer spatial analysis and comparison to landmarks such as gas development wells.

It is hypothesized that due to the local hydrogeology conditions and casing issues reported in the EPA study, contaminants originating from hydraulically fractured wells could be transported by groundwater flow systems to EPA MW01 that had contaminated groundwater. This hypothesis supports the EPA's earlier conclusions from a hydrogeological viewpoint.

3.0 Background of the Study Area

The Pavillion, Wyoming site was chosen to be modeled due to the sufficient amount of available data required to create a groundwater model of the study area. This data is used to obtain parameters for the groundwater model that simulates how groundwater flows over time as the system changes over time due to natural and man-made hydrogeological stresses. Figures A1 and A2 in Appendix A illustrate the hydraulic fracturing process and how casing is a crucial factor in preventing groundwater contamination.

3.1 *Description of the Study Area*

The site of the 2011 EPA investigation linking unconventional natural gas drilling to groundwater contamination in sampled domestic wells near Pavillion, Wyoming has caused major concerns about the potential environmental consequences of this technique. The site is located atop the Wind River formation, which the EPA draft report states "is the principal source of domestic, municipal, and stock (ranch, agricultural) water in the area of Pavillion and meets the Agency's definition of an Underground Source of Drinking Water" (Digiulio et al., 2011). The draft report includes an image of the study area, which is shown in Figure 1. The EPA reports that groundwater sampling in their Deep Monitoring Wells and stable isotope analysis indicate that thermogenic methane—which is not produced naturally and is thus from natural gas wells—was present in both Deep Monitoring Wells as well as a number of local domestic wells (Digiulio et al., 2011). A conceptual groundwater model encompassing these specific wells (outlined in black in Figure 1) was constructed and analyzed with GIS to see if the local hydrogeology would allow methane seepage from gas development wells to contaminate these domestic wells via advective groundwater transport.

When creating a groundwater model with the conceptual-GIS approach, it is necessary to research and collect spatial data that describe the locations of attributes that would be used in the groundwater model. In this case, these include the locations of rivers, topography, natural gas wells, domestic water wells, and the EPA monitoring wells used in the EPA study. Secondly, it is required to collect geological data, gas production history, and information regarding gas wells that would be used as parameters in the groundwater model that cannot be obtained from spatial data. These include geological formations located beneath the study area and their hydrogeological properties such as hydraulic conductivity as well as reported natural gas production records for the wells within the study area. GIS can then be used to specify the groundwater model's parameters (elevation, well location, rivers, etc). This minimizes human error and allows complex models to be constructed in short periods of time.

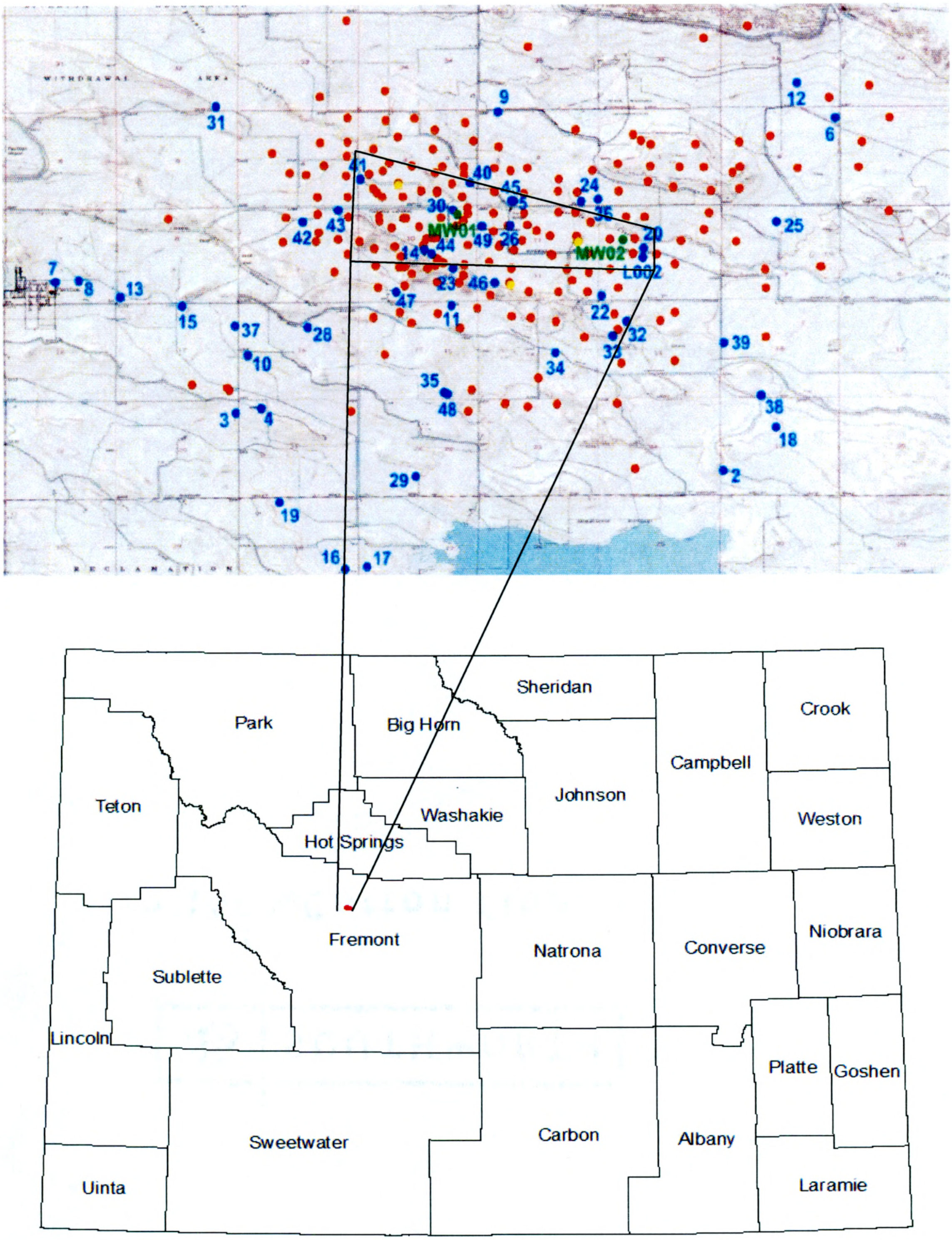


Figure 1: A map outlining the EPA study area with sampled domestic wells, oil and gas wells, and deep monitoring wells reproduced from (Digiulio, et al. 2011). The black outline represents the area the groundwater model simulates. The map shows the location of the study area in Wyoming. Red points represent natural gas wells, blue points represent sampled domestic wells, and the green points represent the two deep monitoring wells that were constructed for the investigation.

3.1.1 *Topography and Hydrology*

A digital elevation model of the area surrounding the EPA study was obtained from the United States Geological Survey's National Elevation Dataset. GIS was used to map the topography and hydrology of the study area from the digital elevation model (DEM) and reported rivers in the area, respectively, with respect to the wells present in the model. The resulting map is shown in Figure 2 and indicates that the topography of the area is quite flat, with a maximum elevation of about 1,652 meters (5,420 feet) and a minimum of 1,622 meters (5,320 feet), generally sloping downwards from west to east.

Fivemile Creek spans the northern section of the selected area, which is used as a boundary condition in the conceptual model. It is part of the Little Wind River tributary of the Wind River Basin and flows southeast from the Owl Creeks (Taucher, et al., 2012).

3.1.2 *Climate*

According to the 2012 Wyoming State Geological Survey report on the Wind/Bighorn River Basin Water Plan Update Groundwater Study, the estimated net annual recharge of the study area is between 1 and 5 inches per year in 2011 and the average annual precipitation from 1961 to 1990 is 6 to 10 inches per year (Taucher, et al., 2012). Assuming this precipitation is accurate in 2011, this would mean about 5 inches of water per year is lost due to runoff and evapotranspiration in the study area. The map (Taucher et al., 2012) showing estimated net annual aquifer recharge is reproduced in Figure 3.

3.1.3 *Geology*

The stratigraphy of the Wind River basin, where the study area is located, is extremely varied in lithology, spatial distribution, and age. Alluvial and sandstone deposits tend to be present in higher, younger formations and can act as aquifers, while older, deeper formations tend to be more minor aquifers and confining units (Taucher, et al., 2012). Under natural conditions, alluvial and sandstone deposits have higher hydraulic conductivity than the deeper shale deposits. As a result, contaminated groundwater can flow through these formations—which are underground sources of drinking water—much faster than in the deeper formations. These hydrogeological parameters vary with geology and in turn influence groundwater flow. Furthermore, hydraulic fracturing changes these parameters as well, normally by increasing hydraulic conductivity. There are two geological formations located underneath the study area: The Wind River formation above the Fort Union formation underneath.

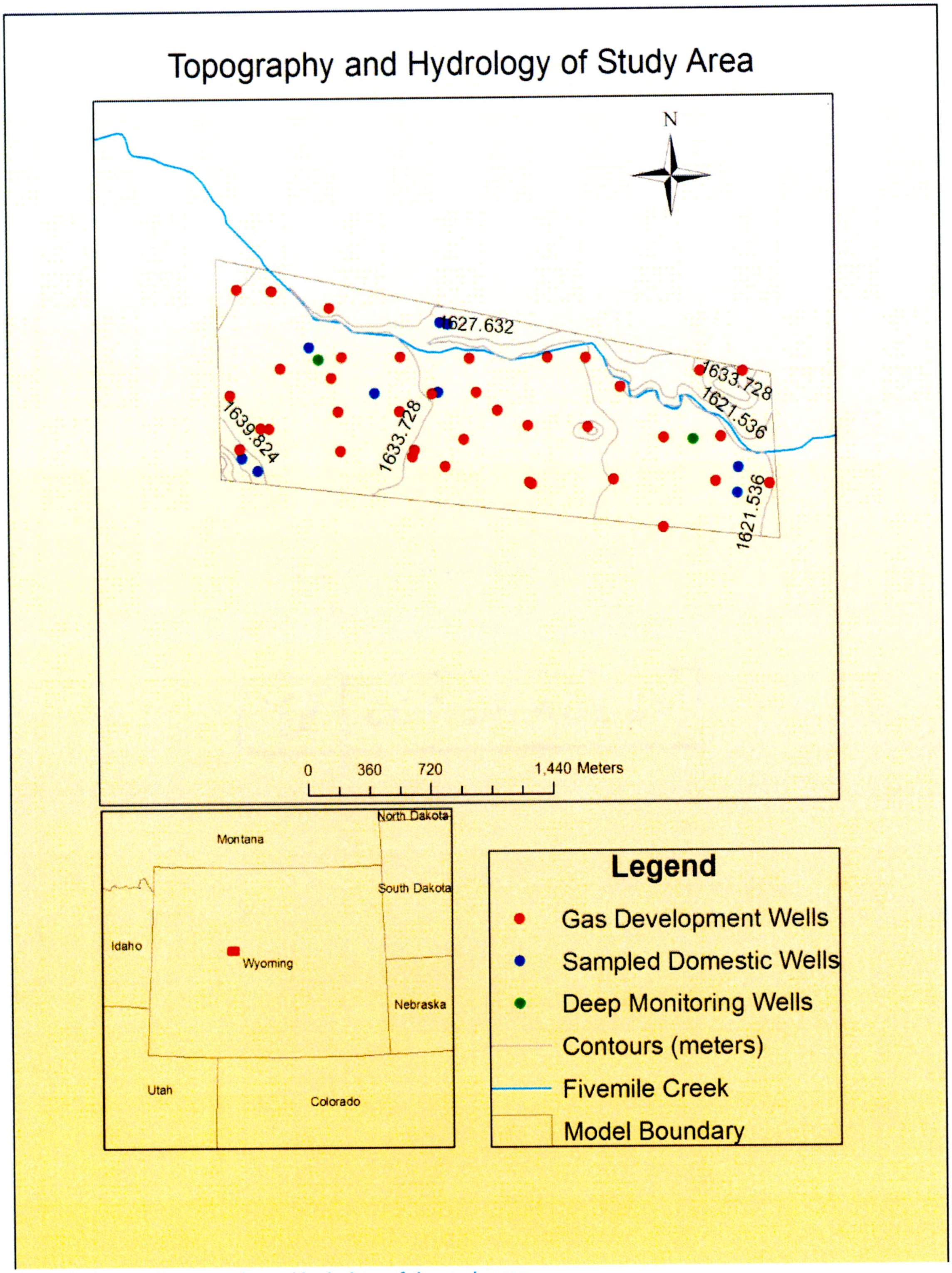


Figure 2: Mapped topography and hydrology of the study area.

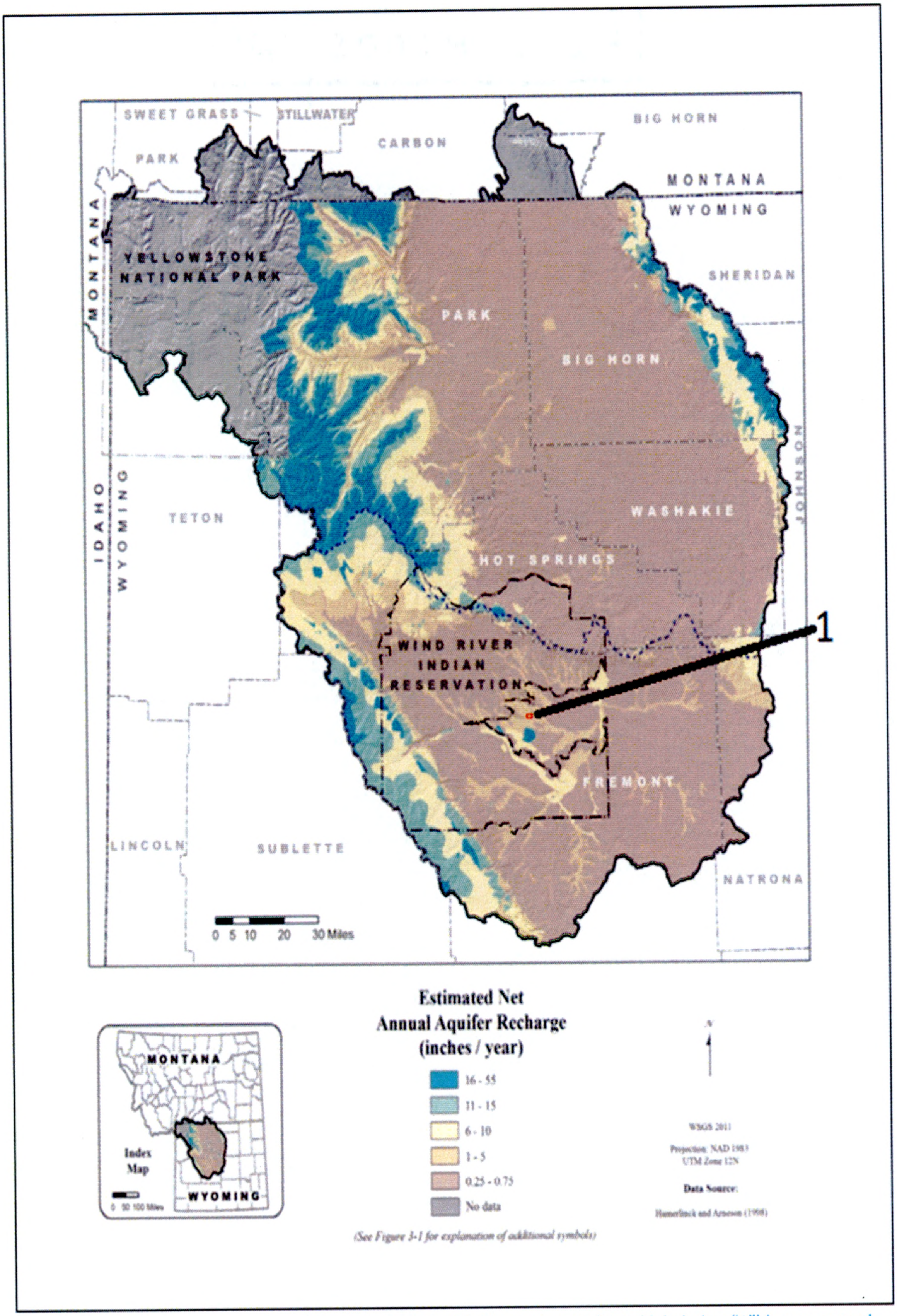


Figure 3: According to this map from (Taucher, et al., 2012), the study area (in red labeled as "1") has an annual recharge ranging between 1 and 5 inches per year.

The Wyoming Oil and Gas Conservation Commission's (WOGCC) website provided borehole data regarding the wells located within the study area, allowing generation of the Wind River formation's and the Fort Union formation's depths (Wyoming Oil and Gas Conservation Commission, N.D.). According to this collected dataset, the maximum thickness of the Wind River formation in this study area is 4,187.7 feet, minimum of 141 feet (if present), and an average of 1,333.55 feet, while the maximum thickness of the Fort Union formation is 3,850 feet, minimum of 270 feet (if present), and an average of 1,392.219 feet. The average top elevation for the Wind River Formation is 2,145.208 feet below the ground surface and the average top elevation for the Fort Union Formation is 3,457.204 feet below the ground surface. The dataset listed "Wind River Upper" is a geological formation with tops at 0 feet (ground level). It was assumed that this formation had the same hydrogeological characteristics as the Wind River Formation since specific geological makeup was not included in the obtained dataset. This dataset is summarized in Appendix B.

According to the USGS Mineral Resources Online Spatial Dataset, the Fort Union formation is composed of primarily shale, but also includes siltstone, sandstone, coal, and limestone (United States Geological Survey, N.D.). The same dataset lists that the Wind River formation is composed primarily of claystone, along with siltstone, sandstone, and coal. However, the EPA report shows the estimated stratigraphy of the selected study area (reproduced in Figure 4) to be relatively evenly distributed between shale and sandstone (Digiulio, et al. 2011).

3.1.4 *Hydrogeology*

According to the Wyoming State Geological Survey's Wind/Bighorn River Basin Water Plan Update Groundwater Study, the Wind River formation is a major aquifer, while the Fort Union formation is a minor aquifer (Taucher, et al., 2012). This means that there is more water available from the Wind River formation than the Fort Union formation. Little information as far as specific geological makeup of the study site is given for the Fort Union formation in the report (Taucher, et al., 2012), but the stratigraphy outlined in Figure 4 allows the model to assume a relatively even distribution of sandstone and shale down to an elevation of approximately 700 meters (2,296.59 feet). As a result, the Wind River formation is treated as the average of sandstone and shale in the models' hydraulic conductivity, porosity, specific yield, and specific storage unless recorded values were reported for the area. However, this diagram did not extend into the Fort Union formation, which has an average top elevation of about 1,913 feet from the reported stratigraphy data. As a result, the Fort Union formation was treated as an extension of the Wind River formation's interbedded geology. Since the USGS Mineral Resources Online Spatial Dataset reports the Fort Union formation primarily of shale as well as siltstone, sandstone, and coal (United States Geological Survey, N.D.), the average of sandstone and shale parameters is able to take into account at least part of the heterogeneity (varying hydrogeological characteristics) of the formation. Furthermore, the stratigraphy logs from the WOGCC did not detail the specific geologies within the formation at the indicated depths; it listed the formation that was present and in lettered sections where applicable (See Appendix B). The hydraulic fracturing of the gas development wells would alter these parameters as well.

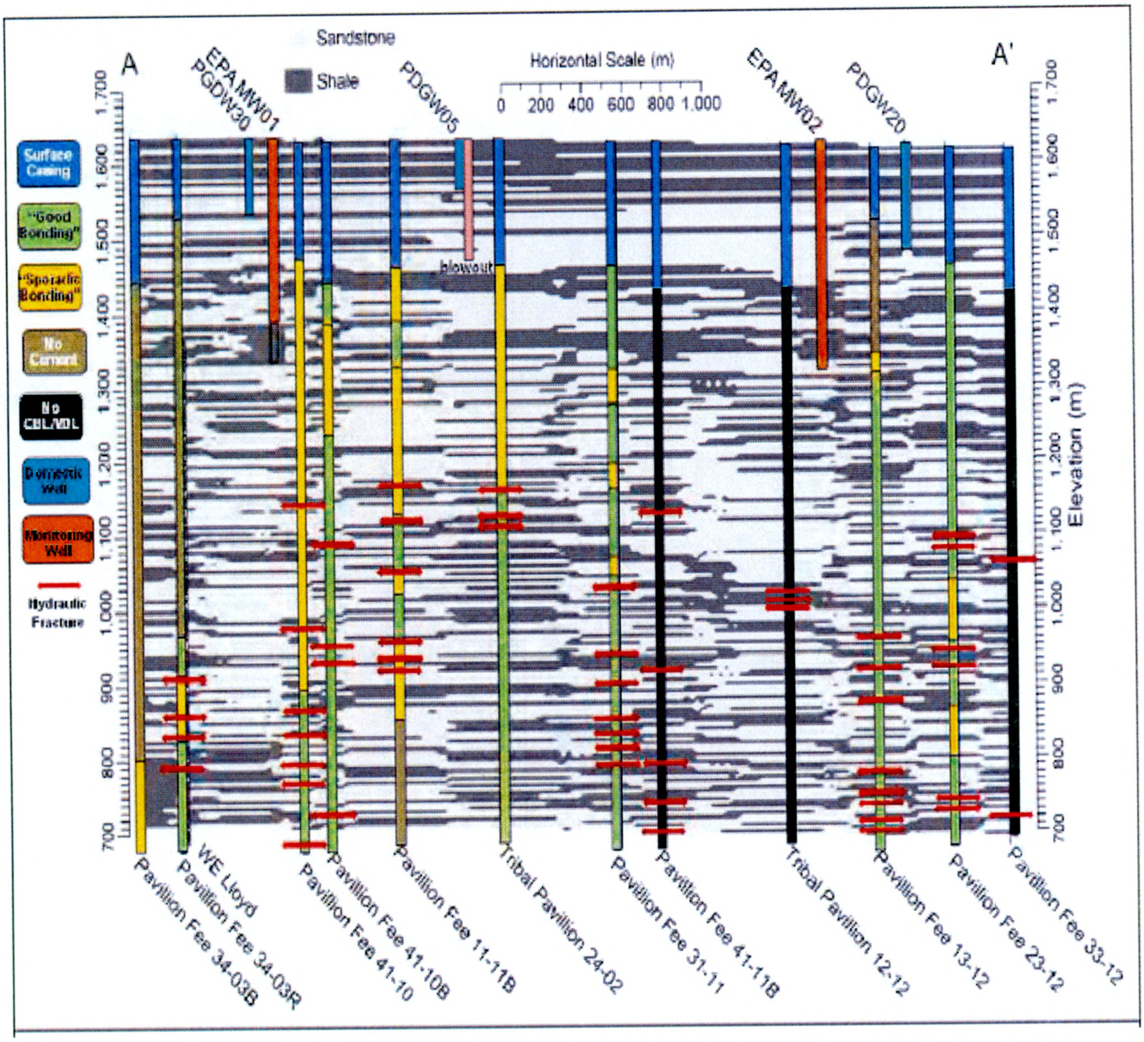


Figure 4: The geology of the EPA study area was reported by (Digiulio, Wilkin, & Miller, 2011) to be relatively evenly distributed between sandstone and shale. This interbedded geology was represented in the model by averaging sandstone's and shale's hydraulic properties. This illustration goes down to an elevation of about 700 meters. The groundwater model assumes that this geology represents the Wind River formation. However, this does not go down to the Fort Union formation. Due to lack of complete data, the Fort Union formation is treated as an extension of the Wind River formation. This graph also reports on the casing depths of the wells. "Bonding" refers to how well the cement seals the space between the casing and the borehole where contaminants can escape from the well.

3.1.5 *Gas Production*

According to the dataset acquired from the WOGCC, there are 38 natural gas wells located within the selected study area. Some wells' production history was recorded since 1981, while others started in later years. These wells may have been producing prior to 1981, but this information was not available in this dataset. The deepest gas producing well was measured to extend 6,482 feet below the ground surface, while the shallowest gas producing well extended 3,180 feet below the ground surface. Three of the 38 wells' production data are graphed in Appendix C. These three sets were chosen because the wells were in close proximity to reported groundwater contamination.

Furthermore, well casing is used to prevent fluids entering shallow groundwater aquifers from oil and gas wells. The EPA report stated that certain wells had casing with poor and/or sporadic bonding below surface casing, which describes how well the casing is cemented to the borehole where natural gas is extracted through in order to block fluids from leaking out of the borehole. Some wells sections lacked cement completely (Digiulio et al., 2011). This dataset reports surface casing depths for the 38 gas development wells ranging from 0 to 645 feet beneath the ground surface. Since these casings are made to block contaminants from leeching into the surrounding groundwater flow systems, they affect the movement of particles within the model where casing is properly constructed and maintained. The casing size decreased with depth at varying intervals, so it was assumed that the well screens (areas where gas extraction and hydraulic fracturing occurred) were present when casing size decreased (see Appendix B) .

4.0 Methodology

The creation of groundwater models with GIS data can be a complex process depending on the type and amount of data required and available. However, once the spatial data that contains elevation, river, and well location is collected and tailored to the spatial extents of the groundwater model (i.e., removing irrelevant data points that do not fall within the model's boundary), the model production process is shortened significantly and produces highly-detailed models. In order to create a realistic groundwater model of the study area, it is necessary to acquire accurate data about the parameters listed in the previous chapter (hydrology, topography, well locations, etc). The data required for this thesis was available through published research and online databases as outlined in section 4.1.1. The methodology was structured to meet the two objectives of this thesis and is outlined as follows:

1. Collect spatial data regarding locations of gas development wells, sampled domestic wells, deep monitoring wells, rivers, and a digital elevation model of the area (see section 4.1.1).

2. Collect geological and gas production data regarding sub-surface characteristics that would make up the hydrogeological parameters in the model (gas production history, reported specific yield, reported hydraulic conductivity; see section 4.1.1).

3. Use GIS to create contour lines from the digital elevation model of the area and process the spatial data to remove features that do not apply to the groundwater model (e.g., wells that are outside the model's chosen boundary and the sections of Fivemile Creek that are outside the model's extent).

4. Use the GIS-Conceptual model approach to use GIS data to create coverages for GMS to use. This involves importing the GIS data in the format of shapefiles into GMS and converting them to coverages representing contours, Fivemile Creek, gas development wells, sampled domestic wells, and EPA monitoring wells. Enter the gas production data into WEL and MNW coverages representing the gas development wells. Create 2D scatter point set from contour coverage containing elevation values.

5. Convert the contour 2D scatter set into a Triangulated Irregular Network (TIN) (Not in GIS-conceptual model approach; see section 4.2.3.1).

6. Use the TIN to define the head-stage attributes in the contour coverage and both the bottom elevation and head stage in the river coverage representing Fivemile Creek. (Not in GIS-conceptual model approach; see section 4.2.3.1).

7. Continue with GIS-Conceptual model approach by creating a grid frame around the active coverages.

8. Create 3D grid from grid frame with 8 layers and 8,000 feet deep. Generate a new MODFLOW with the grid. Activate the cells in the coverage in order to set IBOUND of cells that are not within the model's extent to be zero.

9. Set starting head for all active cells (where IBOUND is 1) to 5,370 feet, which the model's average elevation. This will account for unknown head values once known ones from the contours are mapped into MODFLOW. Use the map to MODFLOW command to input data from the coverages to MODFLOW. Note that the elevation coverage should apply to all 8 layers.

10. Set starting vertical and horizontal hydraulic conductivity values by averaging reported values under the assumption of 50% sandstone and 50% shale.

11. Run steady state model and calibrate horizontal hydraulic conductivity results to reported recharge values.

12. Change calibrated numerical steady state model to transient model. Specify 391 stress periods reflecting months from January 1981 to July 2013 making the length the number of days in the corresponding month. Set reported (or estimated if unknown) specific storage and specific yield values. Run the transient model with only the river and elevation coverages that were in the steady state model.

13. Add the gas production data by mapping the coverages representing the natural gas wells to the conceptual model. For years prior to gas development listings (including assumed injection periods), list a production rate of 0 cubic feet per day. Both the WEL and MNW packages should be used for proper analysis of how the wells will affect groundwater flow systems. Divide the gas production volume by 600 to convert it to volume of liquefied natural gas since GMS is assuming it is working with liquid water (see section 4.2.2.7). Change horizontal and vertical hydraulic conductivity values, specific yield, and specific storage values to reflect how hydraulic fracturing would change these parameters, and use the parameter estimation tool for unknown values (see section 4.2.2.6). Generate a new numerical model with the updated parameters.

14. Run MODPATH on the MODFLOW solution reflecting natural gas production and generate reverse-direction particles from the EPA monitoring well to trace where the contaminants found at the monitoring well could have originated from in the groundwater flow systems affected by hydraulic fracturing.

15. Export the MODFLOW as a computer aided design (CAD) format and the MODPATH solution as a longitude, latitude, and elevation dataset. Use GIS to map these vectors and particles in order to analyze the MODFLOW and MODPATH results, respectively.

These steps will be discussed in more detail throughout the methodology section.

4.1 *Spatial Data Collection and Organization*

The GIS-conceptual model approach uses spatial data as the primary data-entry method during groundwater model creation; spatial data provides the locations of attributes that act as the model's parameters such as Fivemile Creek, contour lines, and gas development wells. However, the acquired spatial datasets contains information outside of the model's boundary (such as gas development wells throughout Wyoming or rivers other than Fivemile Creek), so these specific points or lines (or features in GIS terminology) needed to be removed from the spatial dataset before being used to create the groundwater model.

4.1.1 *Data Sources*

In order to meet the first objective, spatial data regarding topography, hydrology, and locations of gas development wells within the study area were obtained from the USGS, while domestic drinking water wells and EPA monitoring wells were digitized from the map in (Digiulio et al., 2011) that was previously shown in Figure 1. Gas production history, stratigraphic data, and gas well data were acquired from the WOGCC's website.

4.1.2 *Database Creation and Management*

GIS and database management software were used to spatially select data within the model boundary, which was then compiled into tables. Database software (Microsoft Access) was used to join and query well tables based on well-specific API numbers. This allowed the calculation of average formation thickness from stratigraphy data (averaging the differences of formation top elevations), casing elevation from casing depth (difference of casing depth from well elevation derived from the digital elevation model), and inferred injection rates (calculated from reported injection-production ratios).

The average formation thickness would allow a border between the Wind River and Fort Union formations to be drawn. However, since both formations are sharing hydrogeological conditions, this formation thickness is not essential to this specific groundwater model. If they were separated based on different hydrogeological parameters, then these thicknesses would be needed to define the elevations where one formation ends and the other begins.

Casing elevation is important in this model because it restricts fluid contaminants from leaving wells where casing is present and the bonding between the case and the borehole is adequate. As a result, the MODPATH simulations of contaminants leaving the wells would show little to no movement where casing is present and considerable movement where casing is either absent or has poor bonding to the well. The sections of the wells where casing is absent or thinner are defined as "well screens" in the groundwater model.

In order to accurately simulate groundwater transport, proper injection rates need to be calculated to create realistic MODPATH simulations because higher injection rates would result in farther dispersal of contaminants in groundwater. More detailed and clearer records of hydraulic fracturing and injected volumes need to be listed in the WOGCC's dataset. The specific values of injection rates were calculated, which is discussed in detail in section 4.2.2.7.

4.2 *Groundwater Model Creation*

A total of 4 numerical models were created and ran for this thesis:

1. A steady state model that is calibrated to reported groundwater recharge values
2. A transient model under natural conditions (i.e., gas wells are not added to the model) to see if the model is sensitive to time (only RIV and Time Var. Head packages were run)
3. A transient model containing the influence of gas development wells (with WEL and MNW packages)
4. A transient model with gas wells showing where contaminants located at the EPA MW01 may have originated from.

The area of the conceptual model was created to include the two EPA deep monitoring wells and multiple sampled domestic wells (SDW) that showed signs of methane contamination. Specifically, SDW 20 showed signs of thermogenic methane in the EPA study's isotopic analysis, so the model's eastward boundary extended to include the location of that specific well.

However, since the focus of this thesis is on EPA MW01—which is on the westward side of the model—the eastward extent of the model is not as important as the other extents. Fivemile Creek was selected as the northern boundary. The western boundary was chosen in order to align the lower-left corner with the highest elevation in the area of interest. The eastern boundary was chosen to be at the location of SDW 20 where there is also a slight southwards dip in the river, which would cause steady-state vectors to naturally curve upwards. The southern boundary was chosen to meet the western boundary's peak and to include SDW 20. The area of the defined conceptual model's boundary is 37,925,032.27 square feet (1.3604 square miles). The slope is very slight, with a decline of 100 feet generally moving west to east as mentioned with the topography.

4.2.1 *Boundary Conditions Imported with GIS*

Spatial datasets containing the groundwater models' parameters (contours, Fivemile Creek, gas production wells, deep monitoring wells, and domestic drinking water wells) within the study area were created through digitization and spatial selection methods. Each parameter was exported as a shapefile that contained the geographic locations and values of that parameter, such as contour lines containing elevation values. These shapefiles were then imported into GMS to create coverages that represented different model parameters (such as elevation representing specified head) that would have to otherwise be entered manually.

4.2.2 *Parameter Values*

In order to create an accurate groundwater model of the area to simulate where contaminants originating from natural gas wells would flow, realistic parameter values needed to be obtained and/or inferred from known values used in previous research. Each parameter and how its values were found are summarized in this section.

4.2.2.1 Hydrogeological Layering

A three-dimensional grid was created to represent the Wind River and Fort Union formations. Both were divided into four hydrogeological layers to have a total depth of 8,000 feet below the ground surface to allow a detailed analysis of groundwater flow. This resulted in the grid having 8 layers that were each 1,000 feet deep. The deepest layer, layer 8, was also considered to be a confining bed. This is due in part to increasing pressure with depth as well as the fact that the reported vertical hydraulic conductivities of non-fractured shale and sandstone, groundwater would not move vertically 1000 feet (i.e., pass through layer 8) within the 33-year time frame that the model is representing. Layers 1 through 6 that cover well depths will be considered as fractured geology, while layers 7 and 8 were treated as intact formations.

Although the groundwater model cannot easily delineate the different sandstone and shale formations with the borehole data that is available, the relatively even distribution of the geology would allow an average of the two geological parameters to be used as hydrogeological conditions in the model. Furthermore, the EPA study shows stratigraphy down to an elevation of approximately 700 meters (approximately 2,296 feet), whereas the groundwater model of this thesis extends 8,000 feet below the ground surface in order to include all of the gas development wells in the study area. Due to vague stratigraphic data describing the different formation depths in the WOGCC database, it was assumed that the geology of the two formations were 50% sandstone interbedded with 50% shale.

4.2.2.2 Hydraulic Conductivity

Hydraulic conductivity represents how quickly groundwater flows through geological formations. Reported vertical and horizontal hydraulic conductivity values were used as parameters for intact shale and sandstone. These values are listed in Appendix D (Duffield, N.D.). However, two lists of values were present for hydraulic conductivity (see tables D1 and D2). As a result, both of these values were simulated and showed that they were insensitive in the model. The larger horizontal hydraulic conductivity value was chosen to represent the steady state model because the calibration process resulted in a smaller discrepancy between calculated recharge and assumed reported recharge of 1 inch per year, so these values were averaged and then calibrated to a groundwater recharge of 1 inch per year to represent 50% sandstone interbedded with 50% shale. While the reported values were used to simulate steady-state conditions, fractured conductivities needed to be inferred. The resulting horizontal hydraulic conductivity before fracturing was about 0.345 feet per day, while the resulting vertical hydraulic conductivity before fracturing was about 3.63E-6 feet per day. The values used in each model are tabulated in section 4.2.3.

Hydraulic fracturing can increase the hydraulic conductivity of shale to between 10^{-7} and 10^{-4} m/s (0.283 ft/day and 283.4 ft/day, respectively) (Singhal & Gupta, 2010). Since this data for the specific study area could not be found from the WOGCC's website or other background literature, the approximate average value of 141.875 feet per day was listed as the horizontal hydraulic conductivities of hydraulically fractured layers. These fractured layers are defined where casing was not present and thus listed as well screens where particles are allowed to leave the well. As mentioned in section 4.2.2.1, due to incomplete data, both the Wind River and Fort Union formations are treated as 50% sandstone interbedded with 50% shale. As a result, this assumed fractured horizontal hydraulic conductivity value is a conservative estimate because 50% sandstone and 50% shale would have a higher starting, and thus ending, hydraulic conductivity than 100% shale. The seventh and eighth layers were assumed to remain 50% intact shale and 50% intact sandstone because none of the gas development wells are deeper than 7,000 feet below the ground surface.

The calculation of fractured vertical hydraulic conductivity in layers 1 through 6 was under the assumption that the increase is proportional to the increase of horizontal hydraulic conductivity under 50% sand and 50% shale conditions:

$$\frac{\text{Horizontal Hydraulic Conductivity before fracturing}}{\text{Horizontal Hydraulic Conductivity after fracturing}} = \frac{\text{Vertical Hydraulic Conductivity before fracturing}}{\text{Vertical Hydraulic Conductivity after fracturing}}$$

After the corresponding values were substituted in, the equation becomes:

$$\frac{0.345\ \text{feet/day}}{141.875\ \text{feet/day}} = \frac{3.63 \text{ x } 10^{-6}\ \text{feet/day}}{(\text{Vertical Hydraulic Conductivity after fracturing})}$$

The resulting vertical conductivity of fractured 50% sandstone and 50% shale was approximately 0.00149 feet per day. This parameter was entered into the model for layers 1 through 6 where well screen depths were calculated. Since there was no record of fracturing depths from the WOGCC's website, it was assumed that fracturing occurred at each of the layers covering well screen depths.

4.2.2.3 Specified Head, Observed Head, and Fivemile Creek

Due to the assumption that the geology underneath the study area is uniformly 50% sandstone and 50% shale, elevation values in feet were set as specified head along the contour lines. Starting head was set equal to the average elevation of 5,370 feet in columns that were not intersected by contours and thus had unknown head values. The head of these cells were set to be calculated when MODFLOW was run by setting their IBOUND values to 1.

Observation well data was collected from a USGS report carried out on July 24, 2012 from 11:10 AM to 7:27 PM in approximately 15-minute intervals for MW01 (Wright et al., 2012). This dataset included the depth of the water level below the measuring point (BMP), which was assumed to be ground level. Since elevation was known from the digital elevation model, head was calculated as the difference between elevation and water level depth. However, it is important to note that this is an insufficient amount of observational data (a single day's worth) to use for this time frame of 33 years, thus the sensitivity analysis results should be interpreted with caution. Nevertheless, the observation points were essential in predicting parameters that were not found in the background research such as specific storage and specific yield values after hydraulic fracturing occurred.

Fivemile Creek was set as a boundary condition. Its elevation was set to match the TIN created from the contour coverage. This is done through interpolation of elevation values that are matched to Fivemile Creek's location on the TIN. The TIN creation methods will be discussed in further detail in section 4.2.3.

4.2.2.4 Stress Periods

391 stress periods were created to reflect varying gas production rates, which changed monthly from January 1981 to August 2013. In other words, one stress period was equivalent to one month. The length was set equal to the number of days of the stress period's month and each stress period had a single time step. The transient model's parameters change with each stress

period due to changes in well production rates. The steady state model does not have stress periods since it is modeling natural conditions that have little to no fluctuation over time.

4.2.2.5 Specific Yield, Porosity, and Specific Storage

The specific yield of the Wind River basin ranges between 0.1 and 0.26 depending on the geology with a porosity of 0.3 (Taucher, et al., 2012). As a result, a starting specific yield value of 0.13 and a porosity value of 0.3 (porosity is only used in MODPATH settings) were set for all layers in the transient models. The background research did not find how hydraulic fracturing affects these parameters quantitatively, so the Parameter Estimation (PEST) version of MODFLOW was used to estimate these values in the transient models. This tool runs MODFLOW multiple times using a specified range of values for user-defined criteria (in this case specific yield and specific storage) and compares the calculated head of each model to the observed head to measure the most accurate parameters. In other words, it is analogous to running MODFLOW in reverse to find parameters that would match a specific head value. This tool calculated specific yield to be 0.280124 when compared to observational data in the third model reflecting natural gas development and hydraulic fracturing. This is a valid assumption since specific yield is always a lower value than porosity (National Oceanic and Atmospheric Administration, N.D.).

Specific storage values were not directly reported from the Wind River Basin report, so multiple runs of the model yielded realistic results at 5E-7 ft^{-1}. Since reported values of sound rock (as opposed to fissured rock) is $<10^{-6}$ ft^{-1} (Duffield, N.D.), this value was considered realistic and was used to represent specific storage values in non-fractured layers in the transient models. It is possible for specific storage values to increase as a result of increased pressure through stress, decreasing fluid pressure, and/or gas release from a dissolved or trapped state (Yager & Fountain, 2001). Unconventional gas extraction induces all three of these scenarios through hydraulic fracturing, extraction, and gas and fluid migration, respectively. However, background research could not find the exact values by which the specific storage would change. The transient models simulating gas production take this into account by setting a specific storage of 0.280124 ft^{-1}. This value was estimated by trial and error as well as with PEST tool. 0.26 ft^{-1} is greater than reported specific storage values for loose sand ($1.5x10^{-4}$ ft^{-1} to $3.1x10^{-4}$ ft^{-1}) and fissured rock ($1x10^{-6}$ ft^{-1} to $2.1x10^{-5}$ ft^{-1}) (Duffield, N.D.). This specific storage value reported realistic results in the transient models reflecting natural gas development.

4.2.2.6 Well Production Rates

Monthly well gas production data in cubic feet per day and well screen depth data since 1981 were obtained from the WOGCC's website. In order to reflect a more realistic volume since GMS is assuming the volume pertains to liquids, the volume was converted from gas to liquefied natural gas with a reported liquid-to-gas volume ratio of 1:600 (California Energy Commission, N.D.). These converted volumes were entered into each corresponding gas well in the groundwater model. The wells were assigned screen depths that were calculated as the portions of the wells that had decreased or no reported casing. Both the WEL and MNW well packages needed production readings for the months between January of 1981 and July of 2013. However, most of the wells were not producing since 1981, so the months listed before reported activity (gas production) were listed as zero in order to prevent false production data from being extrapolated. It would be beneficial to know when these wells were

However, injection data for most of the 38 wells was not available from the WOGCC website, with the exception of API numbers 1322313, 1322268, 1322271, and 1322272, all of which only had injection readings for one day. Other wells listed explicitly as injection wells were available in the database but were not located within the study area. Some of the well datasets were branching off of other wells—the production data suggests that these compensated for when the main well stopped producing—so those points were merged with the original wells in order to satisfy the model conditions of one column per well. Also, the specific geographical locations of these offshoots were not available from the WOGCC's dataset, which classified all of the wells as vertical.

The months where the production listing was zero were assumed to be months when hydraulic fracturing occurred (thus assumed to be injection wells for that time) in order to stimulate the well. According to NaturalGas.org, a website developed and maintained by the Natural Gas Supply Association, "Producing natural gas from shale requires about 0.6 to 1.8 gallons of water for every million Btu (MMBtu)" (NaturalGas.org, N.D.). Both the lower and upper bounds of this ratio were used to estimate the volume of water used per fracturing well and divided over the months where production was listed as zero. When converted to cubic feet per day, the ratio of injection to extraction rates is extremely small in both the 0.6 and 1.8 ratios, so the higher injection rate (1.8 gallons per day) was chosen to be modeled.

4.2.3 Model Construction

4.2.3.1 GIS-Conceptual Model Creation with TIN

A TIN (Triangulated Irregular Network) is a surface that is created by interpolating values between known points in order to define spatial variables such as elevation. This tool is extremely useful in estimating unknown values.

The creation of the groundwater model in this thesis incorporates TINs into the GMS 7.1 GIS-oriented conceptual model approach (Aquaveo, 2010). Although the concept of TIN usage to create MODFLOW models in GMS is addressed (Aquaveo, 2013) and used with borehole data regarding stratigraphy, the specific application of TINs to the GIS-oriented conceptual model approach of GMS 7.1 is not listed in the available tutorials. This thesis incorporates this TIN methodology instead of the 2D to MODFLOW layers interpolation method that is listed in the GMS 7.1 conceptual model tutorial (Aquaveo, N.D.) and also uses TINs to automate the manual data entry process that is outlined in the tutorial. TINs were used with stratigraphy data in the GMS 7.1 tutorials, however this thesis illustrates how this methodology can be integrated into the conceptual model to use TIN interpolation techniques to enter and manage MODFLOW parameters.

Specifically, the TIN was used to define the head-stages of the nodes in the contour coverage and both the bottom elevation and the head-stage of the Fivemile Creek coverage. This TIN integration is beneficial to the GIS-conceptual model approach because it allows attributes to be defined automatically in cells where data has not been previously entered. In this case, the elevation of Fivemile Creek was unknown from the original shapefile. Without the TIN, the elevation of each node on the river would have be calculated from an outside source such as a digital elevation model and entered manually through GMS.

In summary, in the GMS 7.1 tutorial, TINs are conventionally used for subsurface stratigraphy data in order to act as a surface elevation that boreholes are attached to. This ensures that the geological reading at each borehole's elevation of 0 corresponds to the ground surface that has changing topography. However, since the subsurface stratigraphy is assumed uniform in this thesis, this specific application of TINs is irrelevant. Instead, TINs are used to define surface attributes (i.e., elevation as head stage in coverage nodes in contours and rivers) in order to automate the manual data-entry methods outlined in the GIS-conceptual model tutorial. This automation allows the creation of high-resolution grids to be achievable and timely.

4.2.3.2 Steady-State Model

The parameters discussed in detail in the previous sections were set in the applicable areas of the steady-state model. Only the river and contour parameters applied to the steady state model, which is made in order to be calibrated to realistic conditions to set the layout of the other 3 sequential models' flow systems. This ensures that the models stemming from the steady-state model will also be realistic. The model's MODFLOW Layer Property Flow (LPF) package's parameters are listed in Table 1 below.

Layer number	Horizontal K (ft/day)	Vertical K (ft/day)
1	0.345	3.63E-06
2	0.345	3.63E-06
3	0.345	3.63E-06
4	0.345	3.63E-06
5	0.345	3.63E-06
6	0.345	3.63E-06
7	0.345	3.63E-06
8	0.345	3.63E-06

Table 1

4.2.4 *Calibration*

Before the steady-state model could be used to generate the transient models, it needed to be calibrated in order to reflect realistic conditions. The calibration process assumes that half of the study area acts as a recharge zone and half as a discharge zone in the steady-state model. Fivemile Creek is the main groundwater discharge area, and it spans throughout the model's east-west extent, which can justify this assumption. Recharge rates for the study area ranged between 1 and 5 inches per year (Taucher, et al., 2012). In order to compensate for this range, three steady state models were run and hydraulic conductivities were calibrated to recharges of 1, 3, and 5 inches per year. However, only the hydraulic conductivity resulting from the 1 inch per year model (0.425 feet per day) fell in the calculated range of 50% sandstone and 50% shale (between 4.28E-5 feet per day and 0.8507 feet per day); the resulting calibrated values of 1.7 feet per day and 1.036 feet per day in the 5 inch per year and 3 inch per year models, respectively, were greater than the 0.8507 feet per day maximum value (see appendix D for details). As a result, the one inch per year model was used to generate the transient models. Proportions of horizontal hydraulic conductivity to calculated recharge were used to estimate hydraulic conductivity values that would reflect a recharge rate of 1 inch per year.

4.2.5 Transient Models

4.2.5.1 Transient Model Without Gas Development Wells

The calibrated steady-state model was then set to run as a transient model. However, the wells were not present in this transient model in order to test the model against temporal variation under natural conditions. The stress periods, specific yield, and specific storage values listed in Table 2 were added to the model, which was then ran. MODPATH was then run to illustrate where groundwater located underneath MW01 could originate from when the geology is intact prior to fracturing.

Layer number	Horizontal K (ft/day)	Specific Yield	Specific Storage (ft^{-1})	Vertical K (ft/day)
1	0.345	0.13	5.00E-07	3.63E-06
2	0.345	0.13	5.00E-07	3.63E-06
3	0.345	0.13	5.00E-07	3.63E-06
4	0.345	0.13	5.00E-07	3.63E-06
5	0.345	0.13	5.00E-07	3.63E-06
6	0.345	0.13	5.00E-07	3.63E-06
7	0.345	0.13	5.00E-07	3.63E-06
8	0.345	0.13	5.00E-07	3.63E-06

Table 2

4.2.5.2 Transient Model Including Gas Development Wells

The third model was set to include the effects of gas development wells on groundwater flow systems, their equipotentials, and flow patterns. The well screens and gas production data in the liquefied natural gas equivalent volume was added to the WEL and MNW packages in MODFLOW and the LPF package was updated to simulate the effects of hydraulic fracturing on layers 1 through 6 as outlined in Table 3. The first six layers include the calculated values reflecting the hydraulic fracturing process as specified in the parameter values section.

Layer number	Horizontal K (ft/day)	Specific Yield	Specific Storage (ft^{-1})	Vertical K (ft/day)
1	141.8740203	0.280124	0.280124	0.00149
2	141.8740203	0.280124	0.280124	0.00149
3	141.8740203	0.280124	0.280124	0.00149
4	141.8740203	0.280124	0.280124	0.00149
5	141.8740203	0.280124	0.280124	0.00149
6	141.8740203	0.280124	0.280124	0.00149
7	0.345	0.13	5.00E-07	3.63E-06
8	0.345	0.13	5.00E-07	3.63E-06

Table 3

4.2.5.3 MODPATH Simulation in Transient Model Including Gas Development Wells

The fourth model was a post-MODFLOW analysis that took the MODFLOW result of the third model and used MODPATH to generate and track tracers within the calculated flow systems and calculate where they would flow. MODFLOW was not actually run in this step, which is why it is not technically a fourth model. This MODPATH analysis simulated four particles representing groundwater containing thermogenic methane from natural gas wells starting in January of 1981 (the first time step) traveling through the system until August 2013 (the last time step) within the cells including and below EPA MW01 for the first six layers where hydraulic fracturing is being simulated. These particles were reverse-direction, which would trace backwards through to model to show where particles that ended up beneath the EPA monitoring well (the starting location) would have originated from (the ending location) in the transient model. MODPATH used 0.3 as the default porosity, which is the reported value in the area, so the value was not changed. However, it could not be determined how hydraulic fracturing would affect porosity, so it was assumed that the value remained constant in all of the layers.

Layer number	Horizontal K (ft/day)	Specific Yield	Specific Storage (ft^{-1})	Vertical K (ft/day)	Porosity
1	141.8740203	0.280124	0.280124	0.00149	0.3
2	141.8740203	0.280124	0.280124	0.00149	0.3
3	141.8740203	0.280124	0.280124	0.00149	0.3
4	141.8740203	0.280124	0.280124	0.00149	0.3
5	141.8740203	0.280124	0.280124	0.00149	0.3
6	141.8740203	0.280124	0.280124	0.00149	0.3
7	0.345	0.13	5.00E-07	3.63E-06	0.3
8	0.345	0.13	5.00E-07	3.63E-06	0.3

Table 4

4.3 *Model Mapping*

4.3.1 *Mapping Groundwater Model Results with GIS*

After the numerical steady-state models were created, flow vectors were calculated by MODFLOW to show groundwater flow systems moving from high head to low head. These results were converted to a Computer Aided Design (CAD) format that was imported into GIS and georeferenced for spatial analysis.

The MODPATH results calculate projected latitude, projected longitude, and elevation of particles representing advective methane transport at each time step in feet. Once converted to meters, these particle sets were mapped with GIS, which then converted these particle tracks into arrows to simplify analysis. MODPATH was only run on the fourth model because there were no wells in the first two models that would act as contaminant sources. This mapping procedure meets the second objective of this thesis.

As this methodology illustrates, GIS is not only used in model creation, but in model analysis as well. This is because GIS can give a better spatial reference and interpretation of groundwater flow systems. However, there are limitations present that GMS can compensate for. For example, GIS has sophisticated symbology techniques that can distinguish the different kinds of wells more obviously than GMS (e.g., large, colored circles to represent the three types of wells as opposed to small, dark circles or well icons). Furthermore, GIS is able to filter out extraneous data included in the model—such as the grid edges—and extract the vectors required to visualize the groundwater flow systems. Although the analyst can turn off the display for these unwanted features, using GIS to filter them out is more efficient in terms of file size and simplicity. Since GMS works in a grid environment, it also distorts the model spatially by assuming a well is located in the middle of the cell. However, GIS is only capable of showing a two dimensional top view of the groundwater flow systems, so GMS is needed to illustrate subsurface flow systems and MODPATH trajectories in the third dimension to show vertical, advective transport of methane dissolved in groundwater.

5.0 Results

5.1 *Steady-State Model*

As mentioned previously, the steady-state model represents natural conditions and attempts to confine groundwater movement within the model. This step is important in the groundwater modeling process because it allows the model to be calibrated to reported recharge levels in order to represent natural conditions.

5.1.1 *Calibration*

Only the 1 inch per year calibration resulted in horizontal hydraulic conductivities that matched the reported ranges. The final calibrated horizontal hydraulic conductivity value in the steady state model was 0.345 feet per day. The calibration methods are outlined in Appendix D. Although the in-out discrepancies were more favorable in the 5 inch per year model, the calibration method was focused on matching reported recharge values as opposed to a zero-flux environment. This would make the resulting models more realistic.

5.1.2 *Flow Simulation*

The calibrated numerical steady-state model with equipotentials and vectors illustrating groundwater flow systems under steady-state conditions is shown in Figures 5, 6, and 7. The mapped top view in Figure 8 reflects the topography and hydrology illustrated in Figure 5 with recharge areas pertaining to high elevation and discharge areas pertaining to Fivemile Creek. Although the final in-out measurement was not zero (-3.5312), it was almost a zero percent discrepancy.

As the map in Figure 8 illustrates, the groundwater flow system tends to follow the elevation pattern under natural conditions. As a result, groundwater starting at the sampled domestic well labeled as 1 would flow northeast and discharge into Fivemile Creek around the area labeled as 2. However, due to the topography, the flow systems change direction at the gas development well labeled as 3, which is a recharge area. Groundwater would tend to dissipate radially away from this well under natural conditions. Depending on the direction of dissipation, the groundwater would either move northwards and discharge into Fivemile Creek or travel farther eastwards before eventually angling northwards farther downstream in Fivemile Creek at the areas labeled as 4.

Figures 5 and 6 illustrate groundwater flow under natural conditions following the general west-east direction outlined in the map. However, vertical movement seems to be inversely proportional with depth. This could be due different flow systems (i.e., local and/or regional) that may be present.

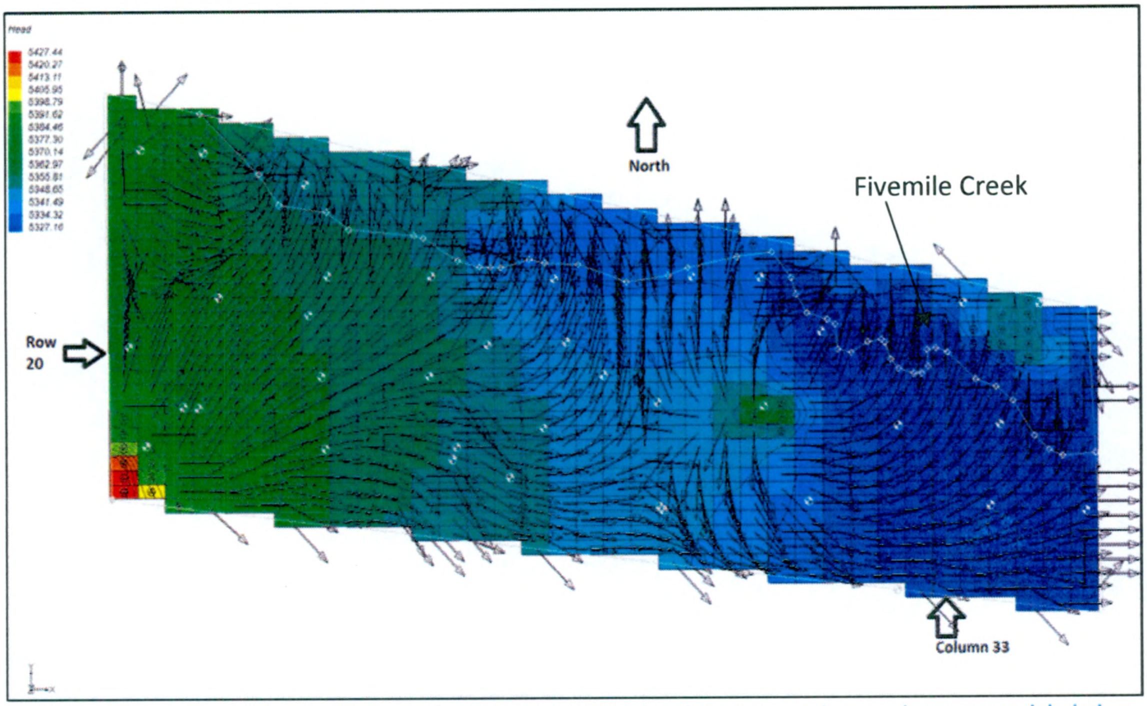


Figure 5: The top view of the resulting steady state model. High head ranges pertain to recharge areas, labeled as 1, such as high elevation areas. Low head areas pertain to discharge zones such as Fivemile Creek. The row view in Figure 4 shows row 20 and the column view in Figure 5 shows column 33.

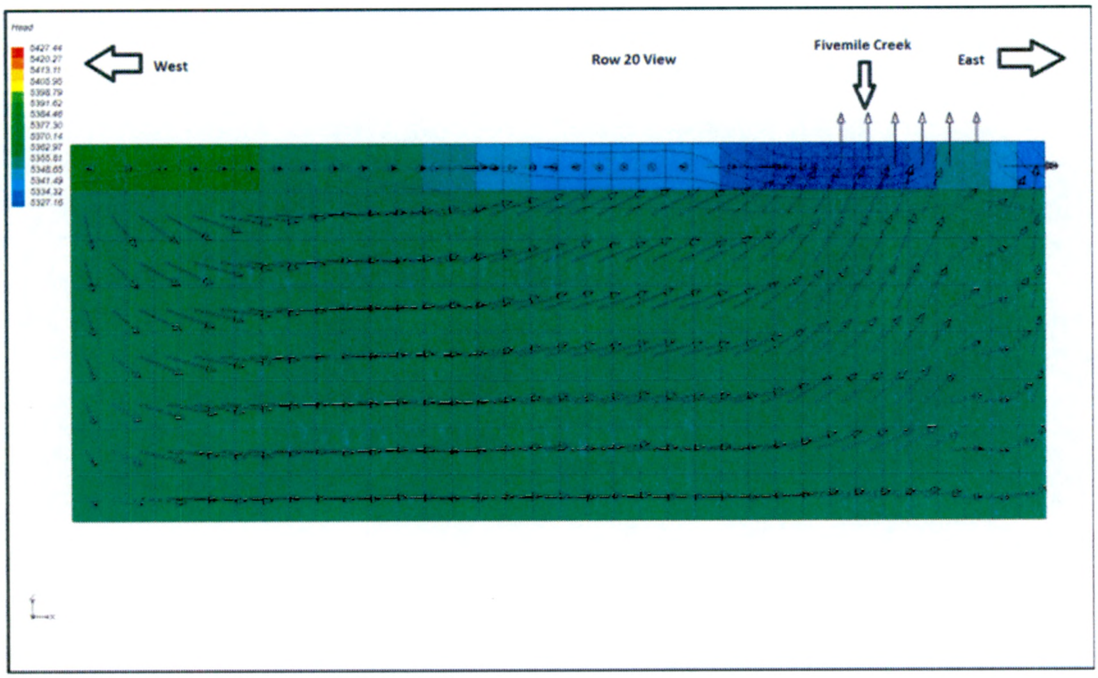


Figure 6: Steady State model facing north (row 20). Groundwater tends to move eastwards towards Fivemile Creek as a discharge area.

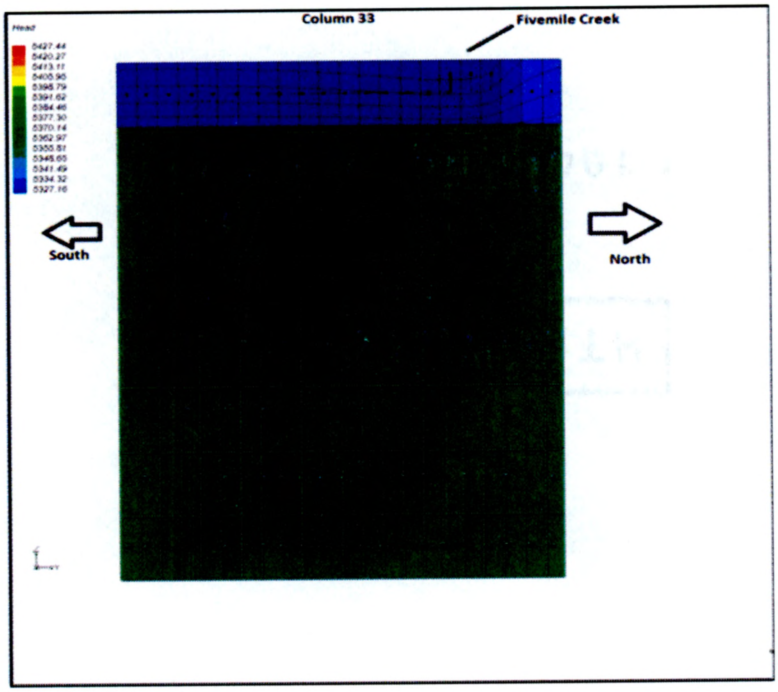


Figure 7: Steady State model facing east (column 33). Groundwater tends to flow upwards towards Fivemile Creek, which is a discharge area.

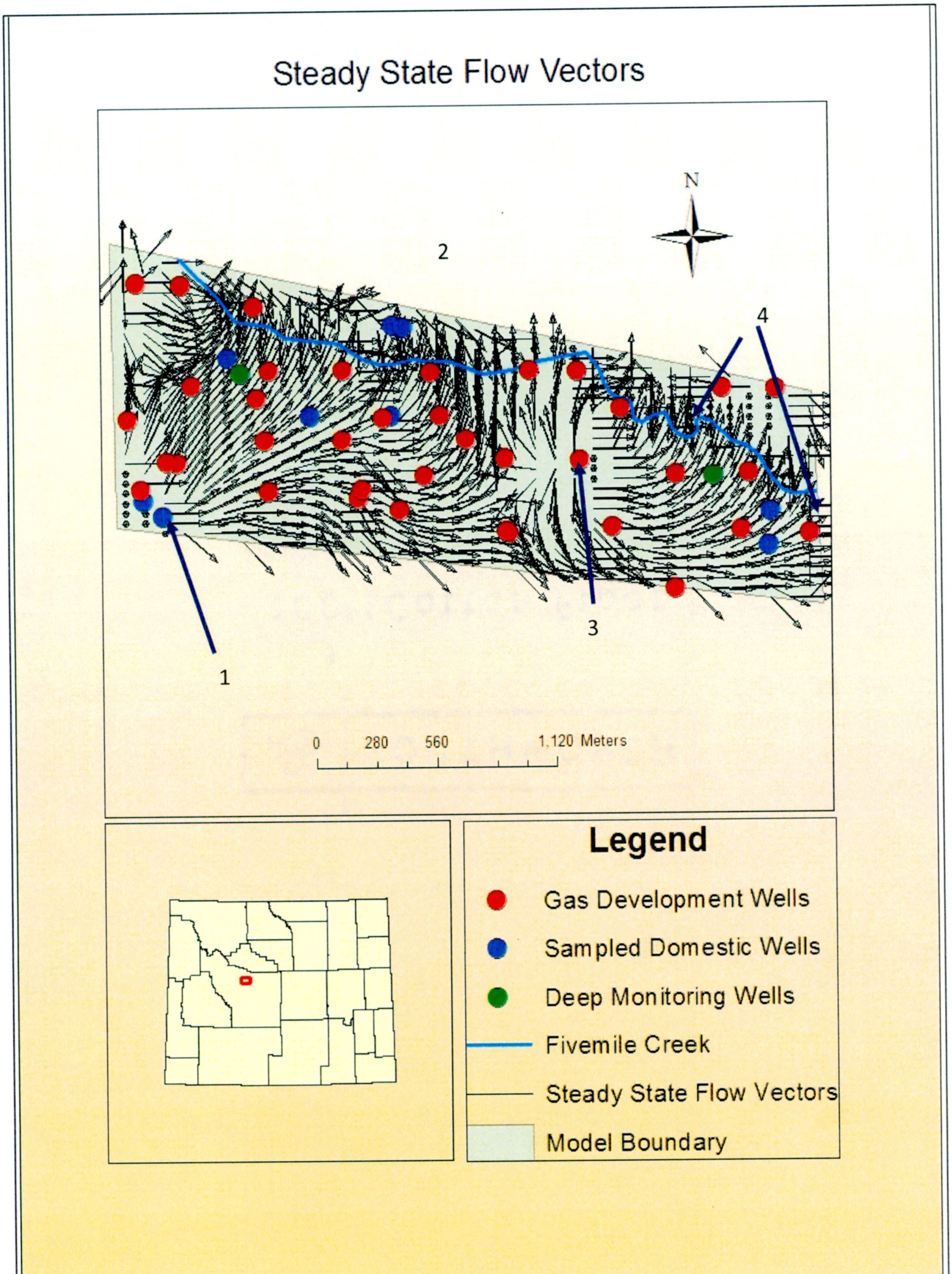


Figure 8: Steady state model vectors mapped with respect to wells within the study area. The groundwater flow systems tend to move from west to east while curving towards Fivemile creek. For example, groundwater would flow under steady state conditions from the sampled domestic well labeled as 1 to the area of Fivemile Creek labeled as 2, while the slight higher elevation at the gas development well labeled as 3 would tend to change groundwater flow to move towards Fivemile Creek at point 4.

5.2 *Transient Models*

The first transient model introduces the temporal factor into the steady state model in order to test whether these conditions would change over time. The second transient model simulates the effects of wells on the groundwater flow systems. Since the extraction and injection rates vary over time, the stress periods changed to represent these variations on a monthly basis. MODPATH tracked particles traveling over the 33-year time span of the second transient model and showed that particles beneath the EPA monitoring well could have originated from a nearby gas development well.

5.2.1 *Transient Model Without Gas Development Wells*

The resulting transient model with natural conditions (i.e., no wells) is shown in Figures 9, 10, 11, 12, 13 and 14. The views reflect the same positions as the views in the steady state model for comparison purposes. The first and last time steps had virtually identical flow patterns and equipotentials representing head values. Recharge zones are labeled as 1 and Fivemile Creek is labeled, just as in the steady state model. This similarity reinforces that the conditions specified in the steady state model are realistic since the model is not sensitive to the time dimension.

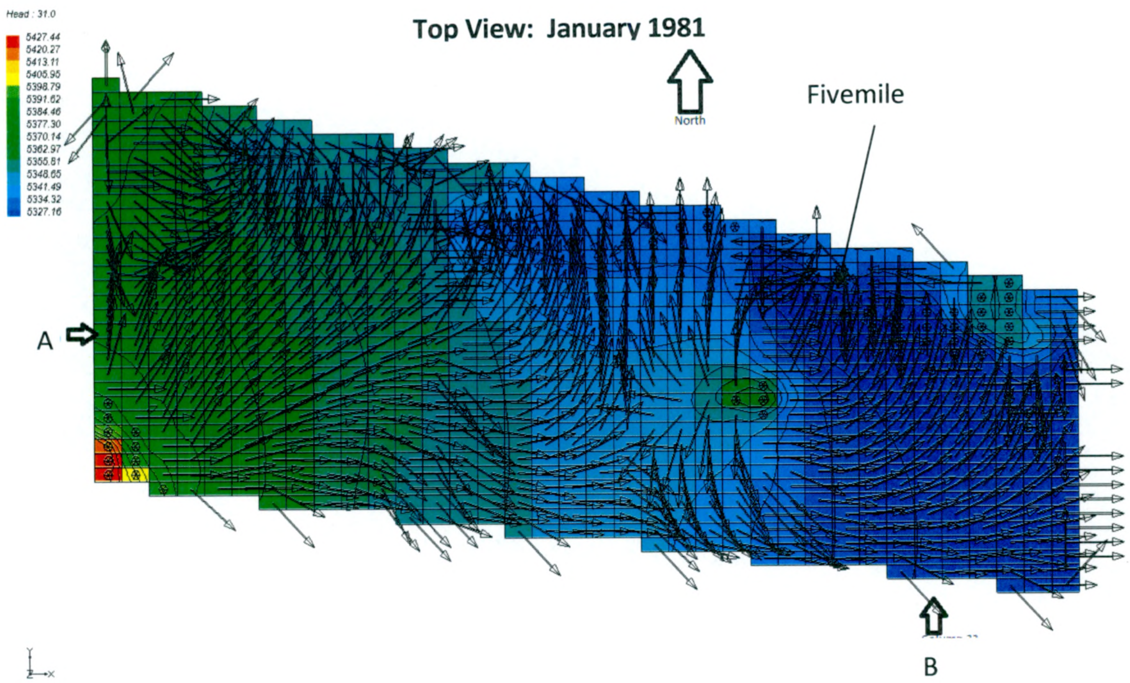


Figure 9: The first time step of the transient model excluding gas development wells. Recharge areas are labeled as 1.

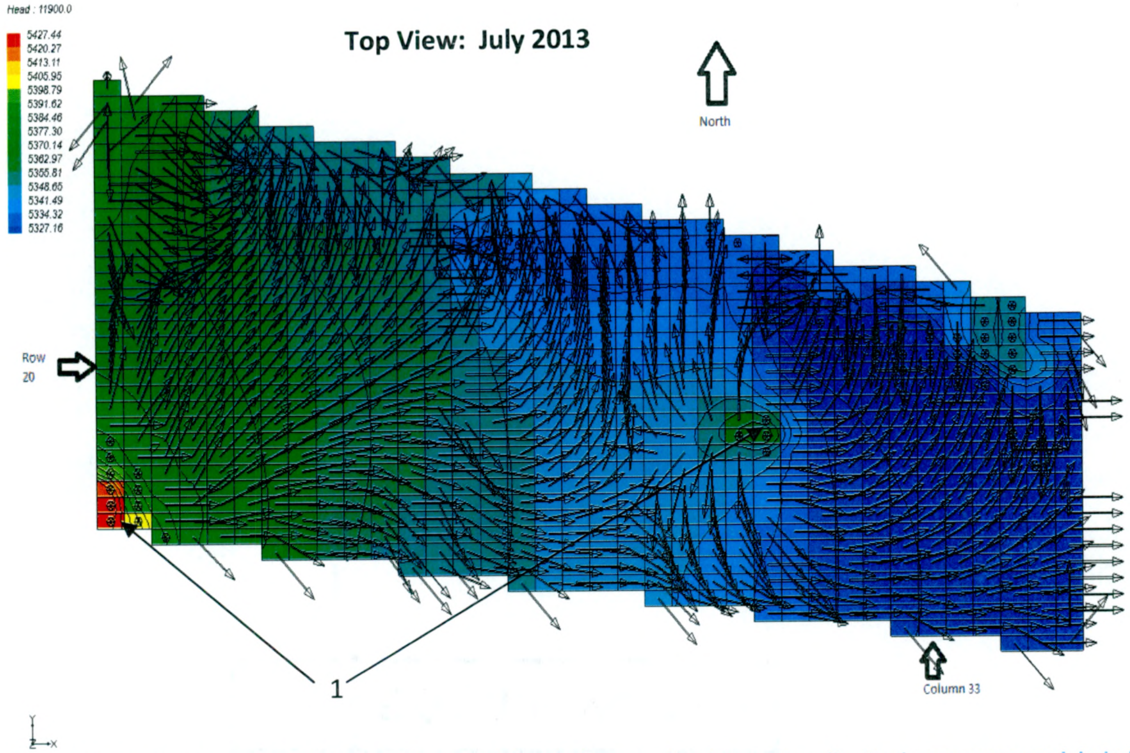


Figure 10: The last time step of the transient model excluding gas development wells. Recharge areas are labeled as 1. Fivemile Creek is a discharge zone. The side views are from row 20 (A) and column 33 (B).

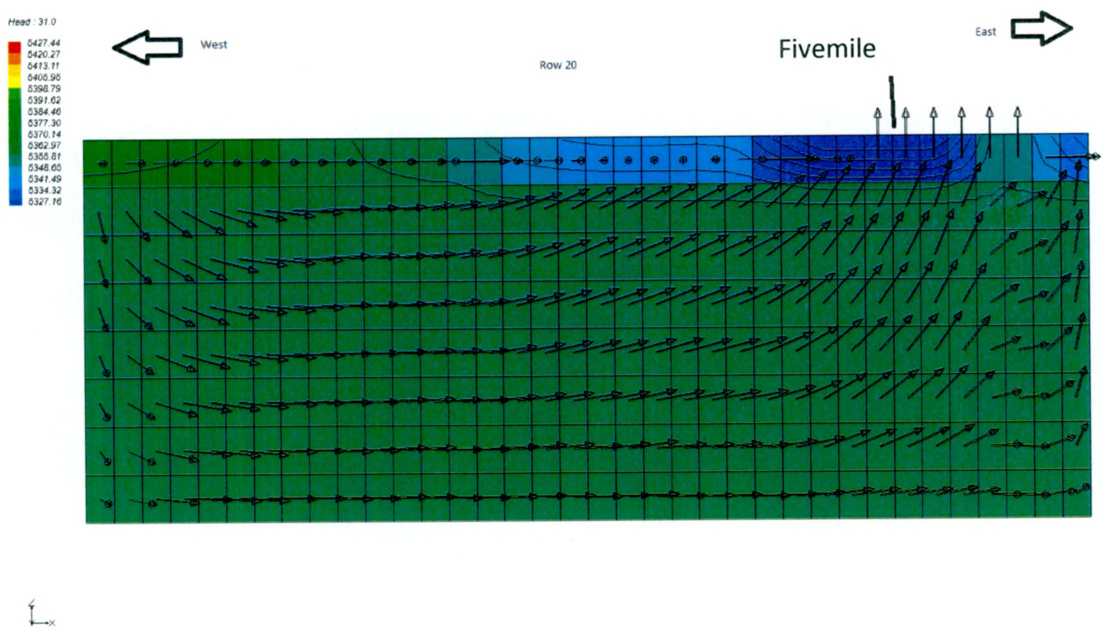


Figure 11: View of row 20 facing north in the transient model lacking gas development wells' first time step.

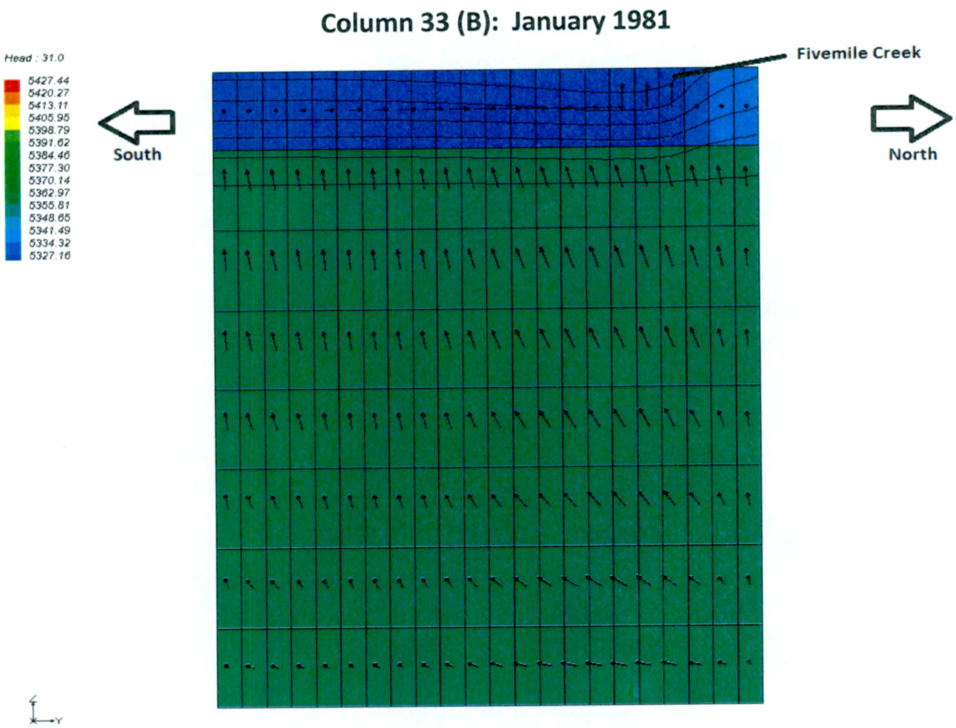


Figure 12: View of column 33 facing east in the transient model lacking gas development wells' first time step.

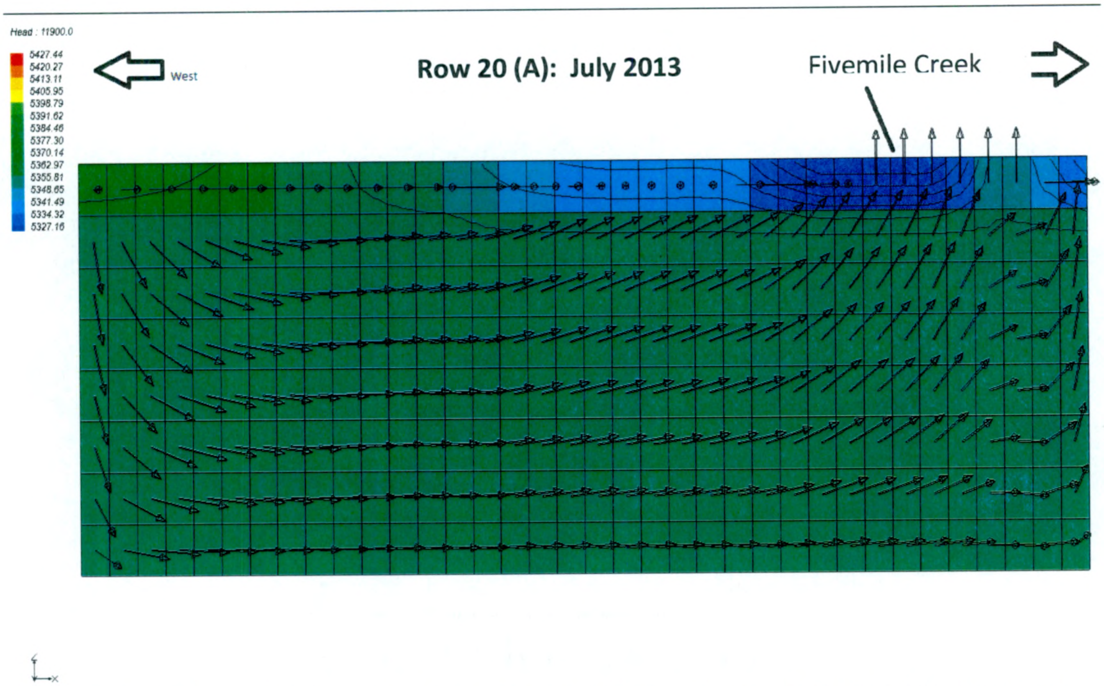


Figure 13: View of row 20 facing north in the transient model lacking gas development wells' last time step.

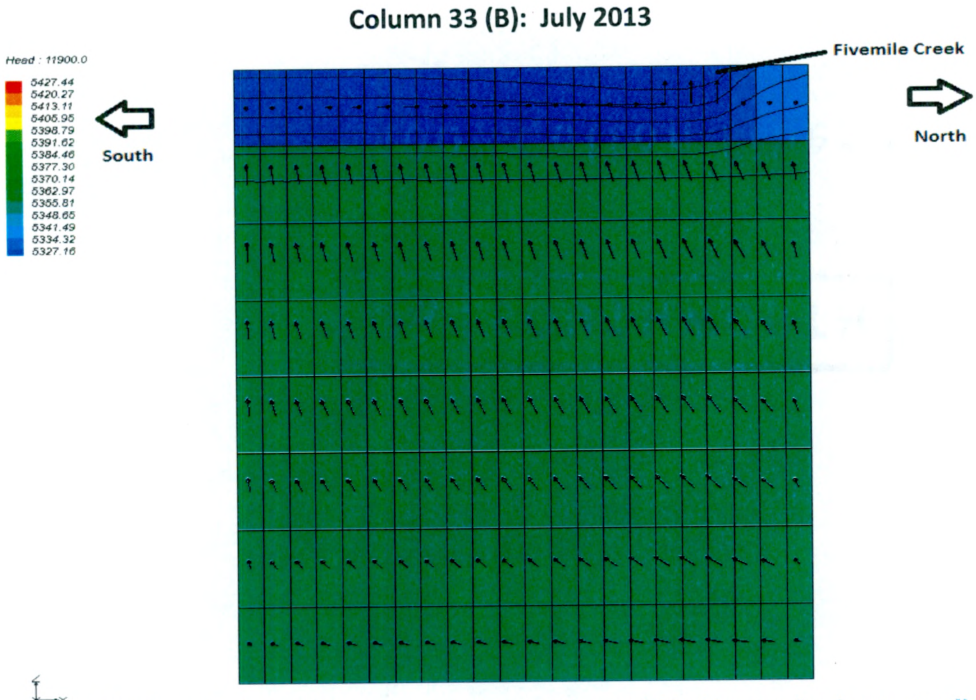


Figure 14: View of column 33 facing east in the transient model lacking gas development wells' last time step.

5.2.2 *Transient Model Including Gas Development Wells*

The first and last time steps of the transient model that included gas development wells, which was generated from the first transient model, are shown in Figures 15, 16, 17, 18, 19, and 20. These figures are at the same locations as the previous transient and steady state models, so the flow vectors and head values can be compared.

The resulting model shows that the gas development wells have an effect on the groundwater flow systems in the area. Injection patterns tend to direct groundwater flow patterns away from the wells, while extraction draws groundwater towards them. Also, areas with higher concentrations of wells (towards the west) show larger changes in groundwater flow than areas with fewer wells (towards the east). Figure 15 shows how injection at the well labeled as 1 alters the flow pattern near Fivemile Creek. This was the only well that was reported to be active in 1981. Figure 16 indicates that groundwater is flowing away from a gas development well (which is represented by a yellow square), which a sign of injection.

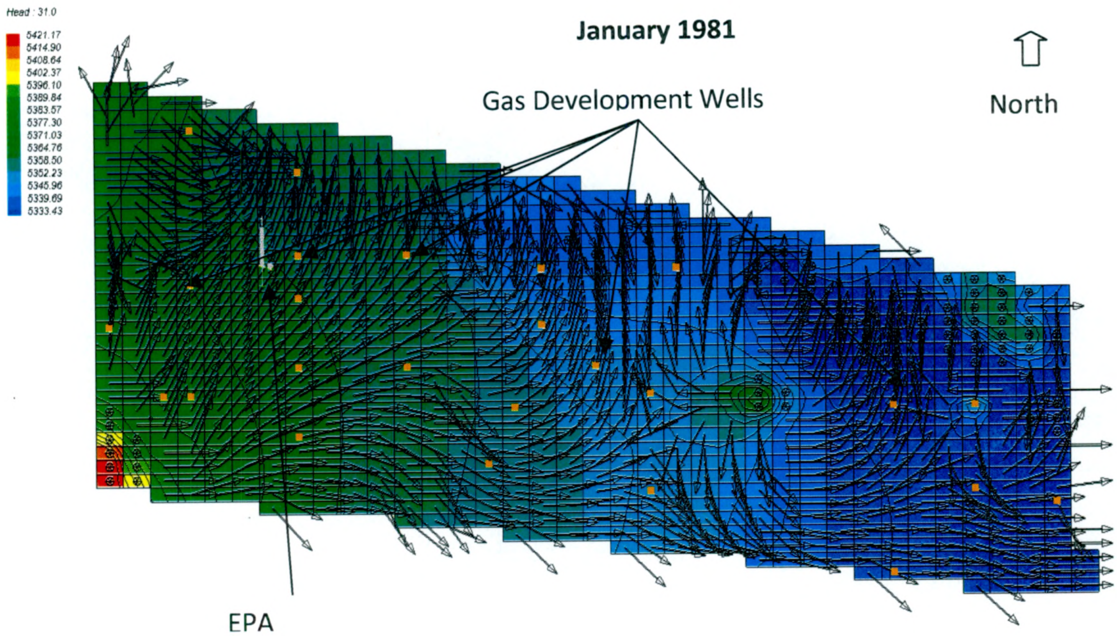


Figure 15: First time step of transient model with natural gas wells, top view. The flow systems are relatively unchanged when compared to the previous transient model due to the relatively little production occurring between January and February of 1981. Gas development wells are represented by yellow squares in the model, however only the well labeled as 1 is active in this time step.

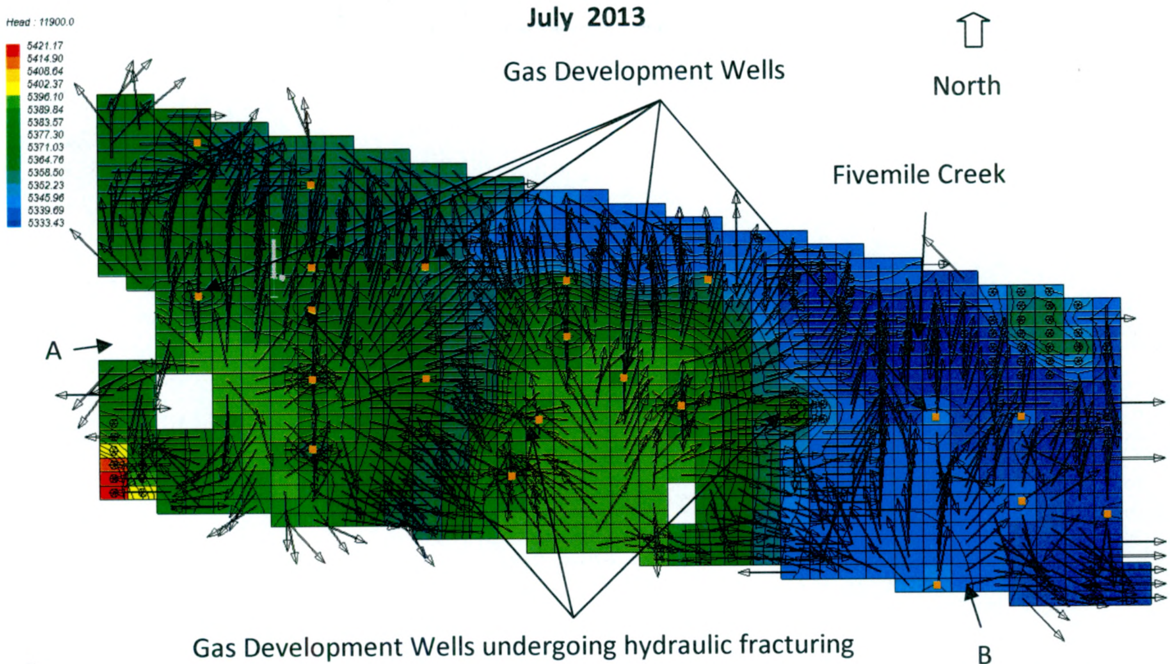


Figure 16: Last time step of transient model with natural gas wells, top view. The flow systems are noticeably affected by the injection process. Gas development wells are represented by yellow squares in the model.

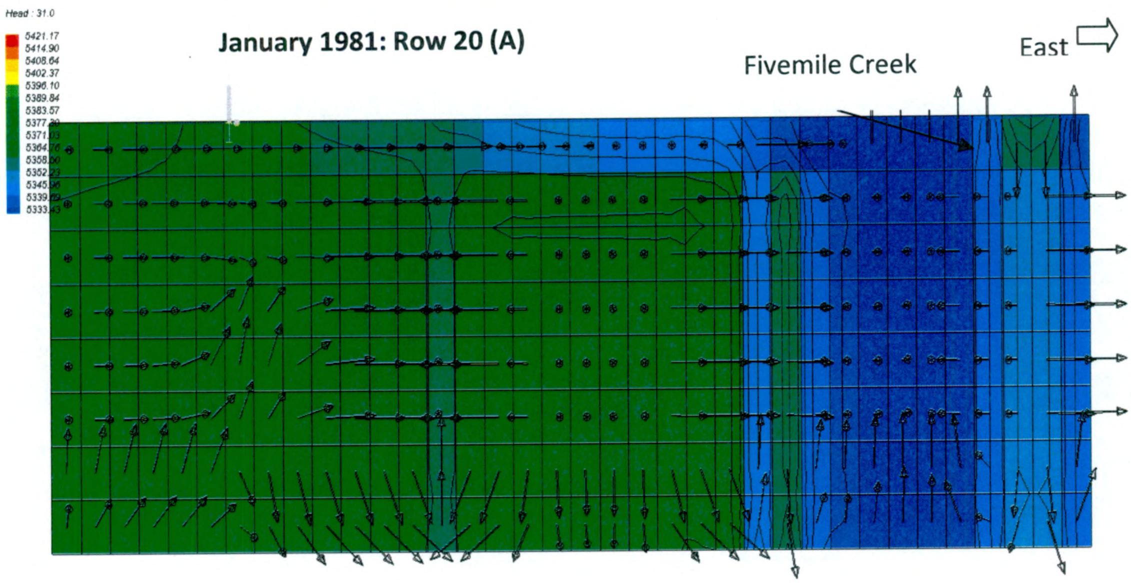


Figure 17: First time step of transient model with natural gas wells, row 20 view. The flow systems are changed from their eastward direction compared to the previous transient model due to the extraction and injection processes during natural gas production.

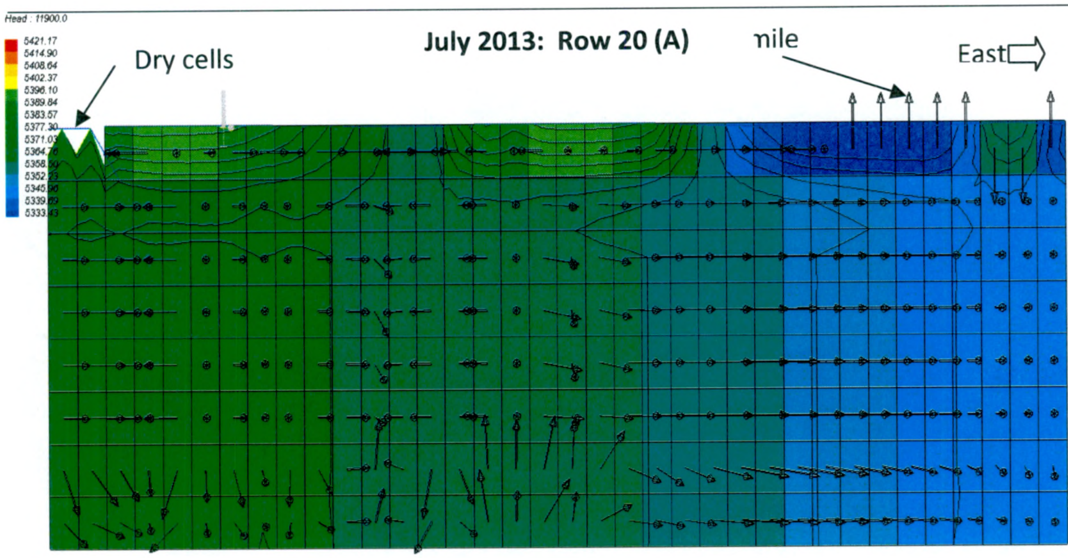


Figure 18: Last time step of the transient model with natural gas wells, row 20 view. The flow systems are greatly changed when compared to the previous transient model due to the extraction and injection processes during natural gas production.

January 1981: Column 33 (B)

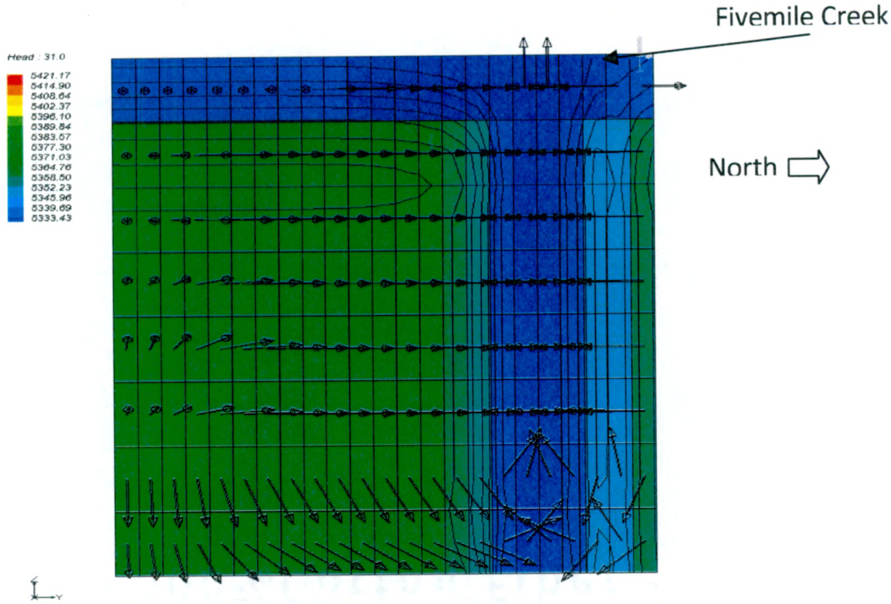


Figure 19: First time step of the transient model with natural gas wells, column 33 view. The flow systems are greatly changed when compared to the previous transient model due to the extraction and injection processes during natural gas production. There is noticeable vertical movement towards the deeper layers.

July 2013: Column 33 (B)

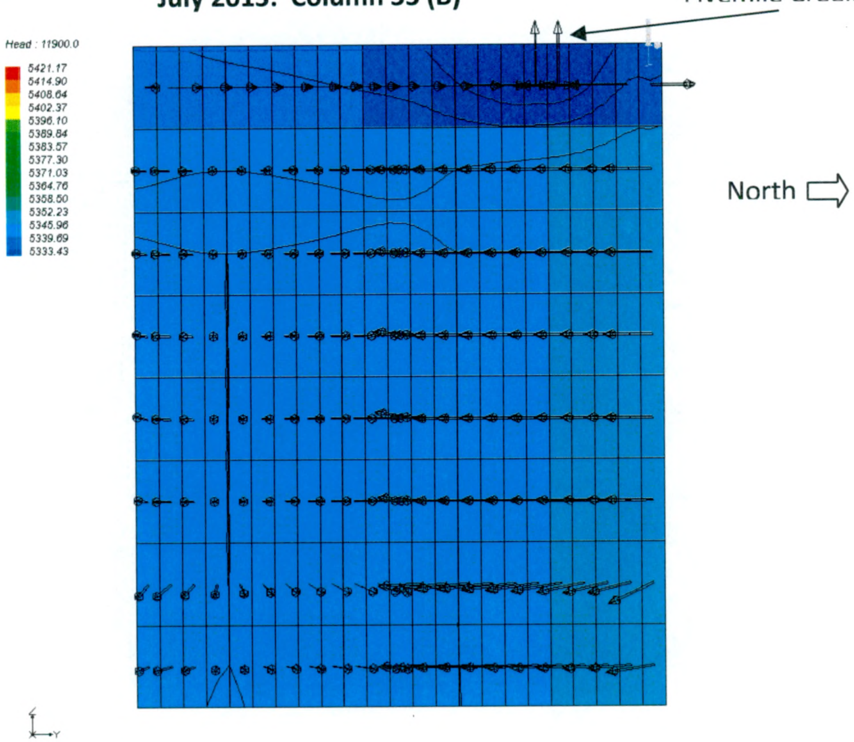


Figure 20: Last time step of the transient model with natural gas wells, column 33 view. The flow systems are greatly changed when compared to the previous transient model due to the extraction and injection processes during natural gas production. The vertical flow movement is not present as opposed to when the wells were not being simulated. Instead, horizontal flow is dominant in this area of the model

A number of dry cells are also present in the model near five gas development wells, which can be due to drawdown during extraction that pulls the water table beneath those respective cells. Since these cells were in the top layer, it may have affected the MODPATH simulation that tracks methane dissolved in groundwater as it flows through the groundwater flow systems. This is because MODPATH cannot pass through dry cells. The MODPATH results will be discussed in further detail in the following section.

The process of injection during hydraulic fracturing forces a high head at the well's location, disrupting the natural eastward groundwater flow systems as can be seen in Figure 16. The flow patterns disperse away from the wells undergoing hydraulic fracturing and towards Fivemile Creek or wells extracting natural gas. Since there is a larger concentration of gas wells on the western half of the model, flow systems are less natural as opposed to their eastern counterparts that have a smaller well density. Since the EPA monitoring well is located near two gas development wells, it is possible that injections following these flow patterns would pass beneath it.

Although the injection rates were calculated as a ratio from the gas production history, the alteration between injection and extraction can have profound effects on groundwater flow systems. For example, as shown in Figure 21, the injection zones near the EPA monitoring well during the last time step—especially API number 1322198, labeled as 1—were extraction zones during other stress periods such as July of 2007.

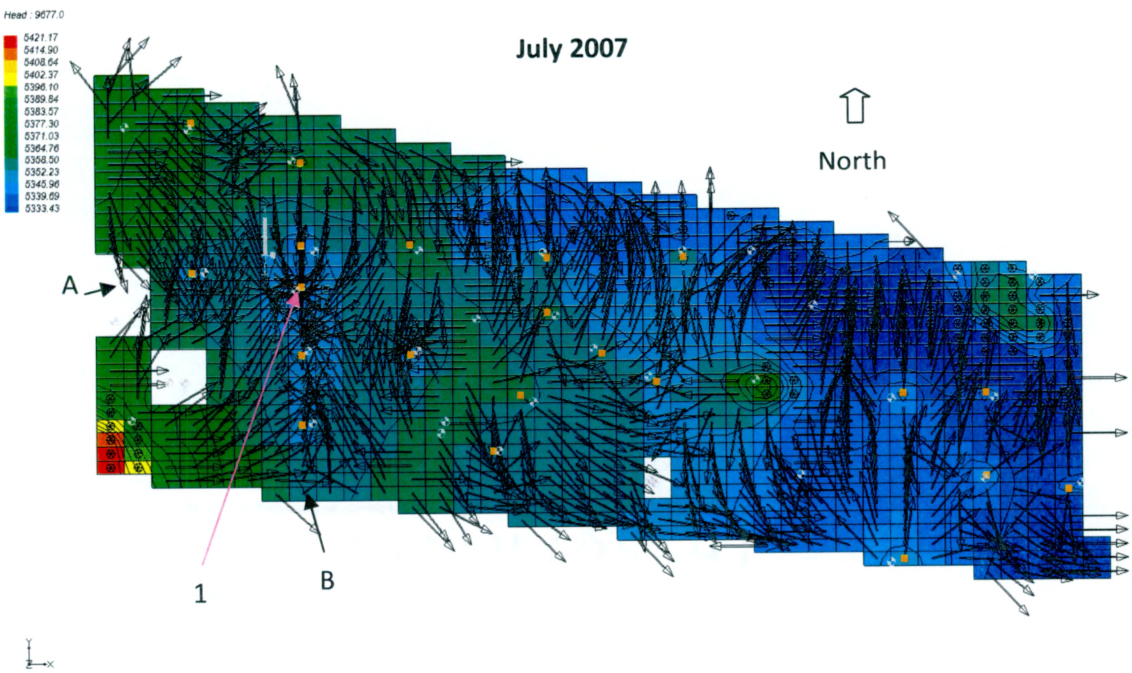


Figure 21: Extraction and injection zones during July 2007. The extracting well labeled as 1 shows a considerably different effect on surrounding flow systems as opposed to the final time step shown in Figure 16 when it was considered an injection well.

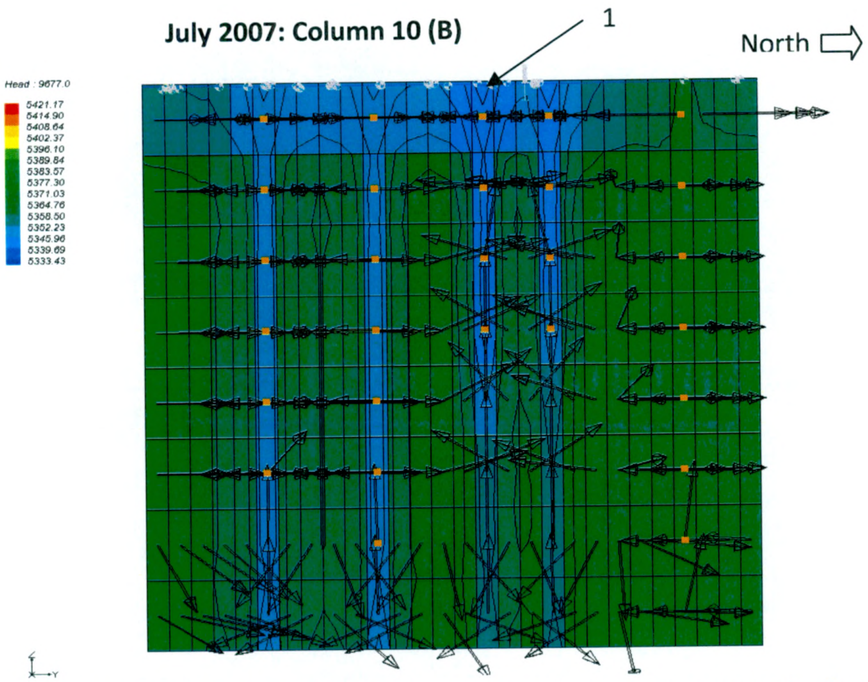


Figure 22: The extraction process from the well labeled 1 causes groundwater flow systems to be directed towards the well. This is a large variation from the injection flow pattern shown in Figures 16, 18, and 20.

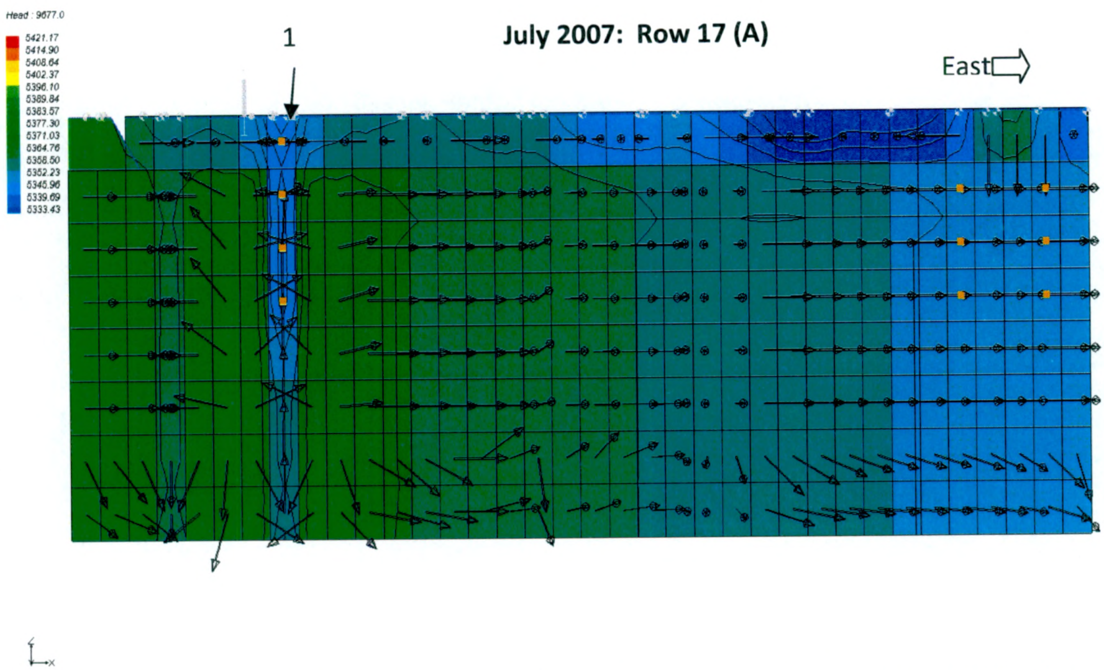


Figure 23: The extraction process greatly altered the groundwater flow system as opposed to well stimulation through hydraulic fracturing.

Conversely, the final time step illustrated previously in Figure 16 shows the same well undergoing hydraulic fracturing, acting as an injection well during that stress period. Groundwater flow systems pointed towards the well during extraction periods, while away from it during times of injection, which is expected. It is important to note the conversion factors of the injection rates; although the assumed conversion from gaseous to liquid natural gas involved a division by 600, the injection rates were not altered due to the reported percentage ratio of volume of water required per volume of natural gas produced.

Furthermore, it was presumed that the seventh and eighth layers would remain as in the steady state and transient models with eastward flow vectors. However, the model predicts that the hydraulic fracturing process would even affect those flow patterns even though the wells themselves do not reach to those depths. This suggests that hydraulic fracturing has both local and regional effects on groundwater flow systems.

5.2.3 *Transient Model MODPATH Tracking Results*

MODPATH results indicate that the changing flow patterns in the model's 33-year time span influenced by injections occurring during well stimulation could act as a pathway for methane-contaminated groundwater to flow beneath one of the EPA monitoring wells in the Pavillion, Wyoming case study. These MODPATH trajectories are shown in Figures 24, 25, 26, 27, 28, and 29.

In order to extrapolate where the methane-contaminated groundwater located at the EPA monitoring well originated from, eight reverse-direction MODPATH particles were generated on the faces of the first six cells underneath EPA Monitoring Well 1 beginning on April 1, 2011. These particles act as tracers that trace back through flow systems from January of 1981 to August of 2013 in order to predict where contaminants (groundwater with high levels of thermogenic methane) at the EPA well originated from. These particles were extracted from the groundwater model and mapped in reference to the sampled domestic wells, gas development wells, and EPA monitoring wells while the head values, flow systems, and grid were not. This makes the MODPATH flow lines easier to analyze. These particles were separated based on their particle index in order to be able to differentiate the different trajectories. Otherwise, all of the 48 starting points (8 particles for 6 layers) would be all together and hard to distinguish. These trajectories were then converted into arrows and mapped in Figure 30. In Figure 26, they are labeled as 2 and show that the contaminants at the EPA monitoring well could have originated from API number 1322198 in deeper locations or from a more southwestern location for the top layer. The upper flow pattern in the top layer, labeled as 2 in Figure 28, tends to follow natural flow systems as illustrated in the steady state and first transient models, which is a good indicator that the model was able to simulate well casings properly. However, if the casings were poor and sporadic as the EPA report claimed, the flow patterns in the first layer may be considerably different. Also, the dry cells labeled as 2 in Figure 27 may have influenced the trajectory calculated by MODPATH.

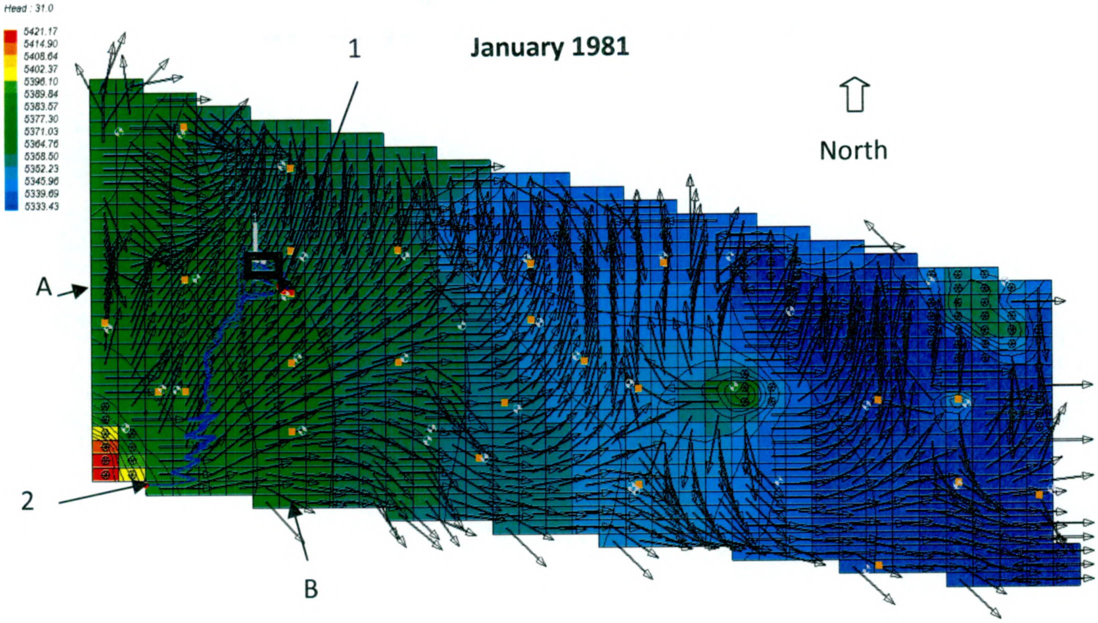


Figure 24: MODPATH analysis produces trajectories in blue that illustrate where groundwater flow patterns would carry methane. This result illustrates that contaminants at the EPA MW01 (outlined in black) could have originated from two locations: API number 1322198 to the southeast labeled as 1 or a further southwest location labeled as 2. However, this could be influenced by dry cells present in the later time steps. Green points represent a particle's starting location (the monitoring well) and red points represent the ending location (the potential origin).

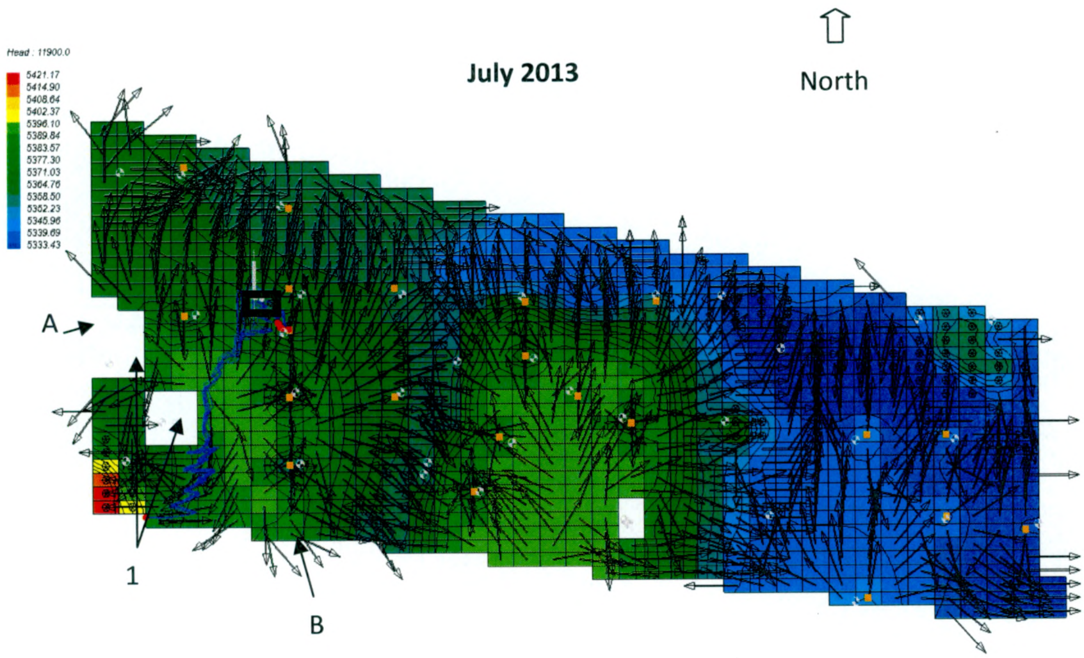


Figure 25: The last time step of the MODPATH analysis shows dry cells, labeled as 1, created by gas development wells that may have conflicted with MODPATH trajectories. If proper data was available, these dry cells could be avoided and may yield different MODPATH results.

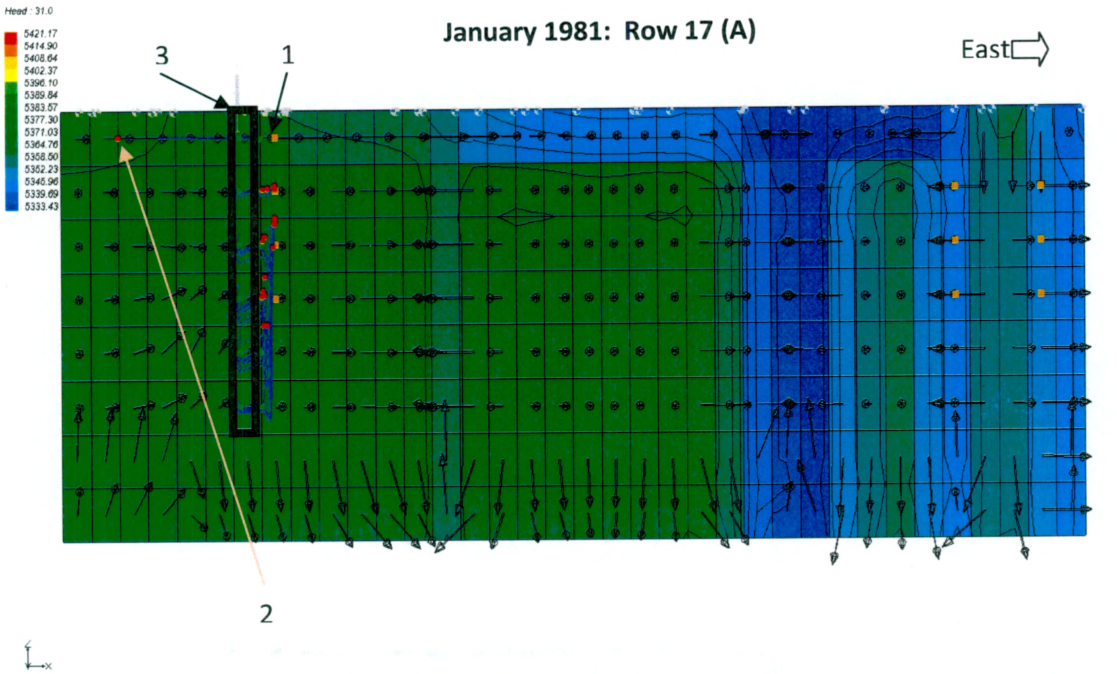


Figure 26: In the first time step in row 17, MODPATH particles illustrate deep groundwater at MW01 containing methane, outlined in black and labeled 3, may have originated from the natural gas well labeled as 1 or shallower groundwater coming from the west. Starting points are green within the box (MW01) and ending points are red (predicted starting locations labeled as 2).

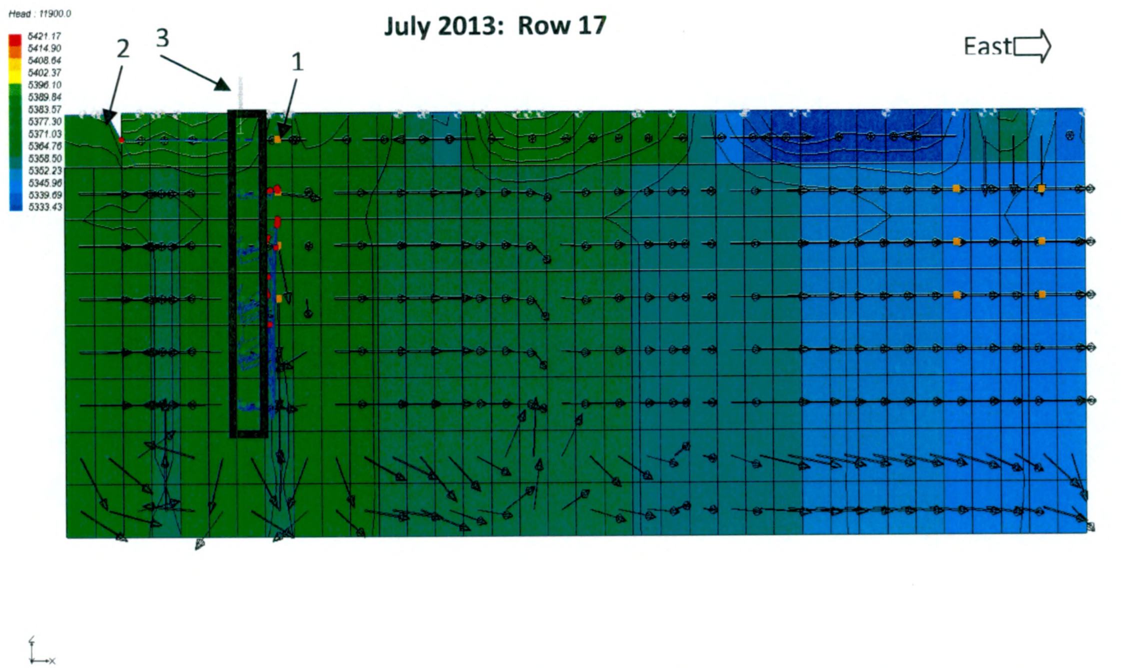


Figure 27: The MODPATH particles in the top layer may have been influenced by dry cells in the resulting model labeled as 2. Deeper particles beneath the EPA monitoring well, outlined in black and labeled 3, were traced back to the gas development well labeled as 1.

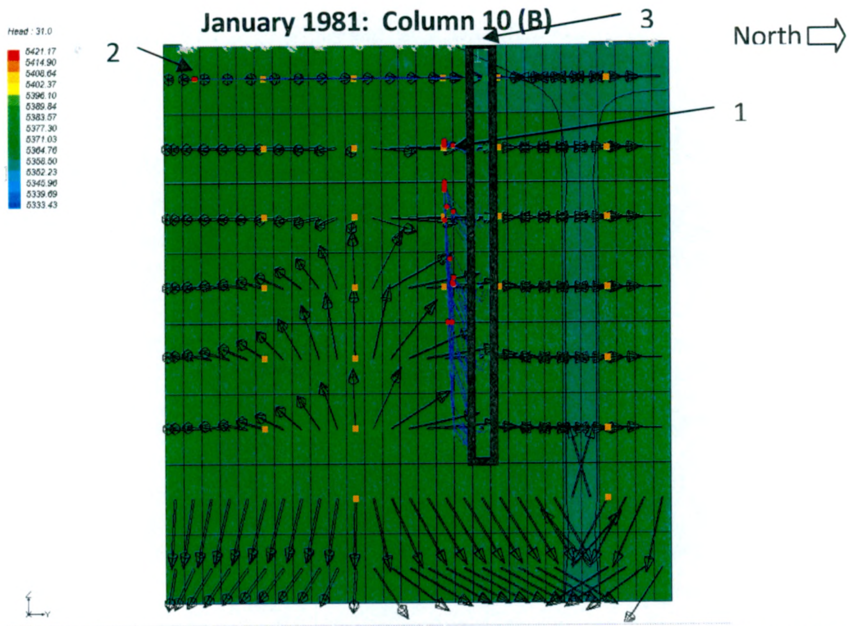


Figure 28: MODPATH trajectories from a column view (facing east) show deep flow systems can carry contaminants from a gas development well labeled as 1 (represented by yellow squares) beneath the EPA monitoring well, outlined in black and labeled 3. Shallow flow systems are traced back to a more southwestern area labeled as 2. Green points represent a particle's starting location (MW01, which is outlined) and red points represent the ending location (the predicted origin).

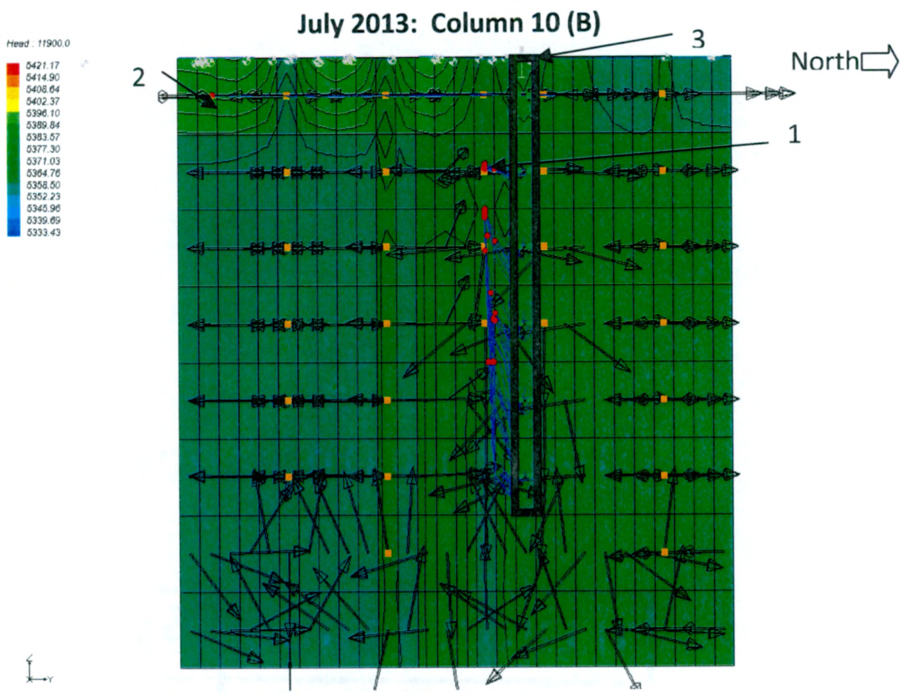


Figure 29: The column view shows that MODPATH calculated the starting locations of methane under the EPA monitoring well, which is outlined in black and labeled 3, could have originated from a gas well labeled as 1 in deep systems or further to the south at area 2 both shown by red points.

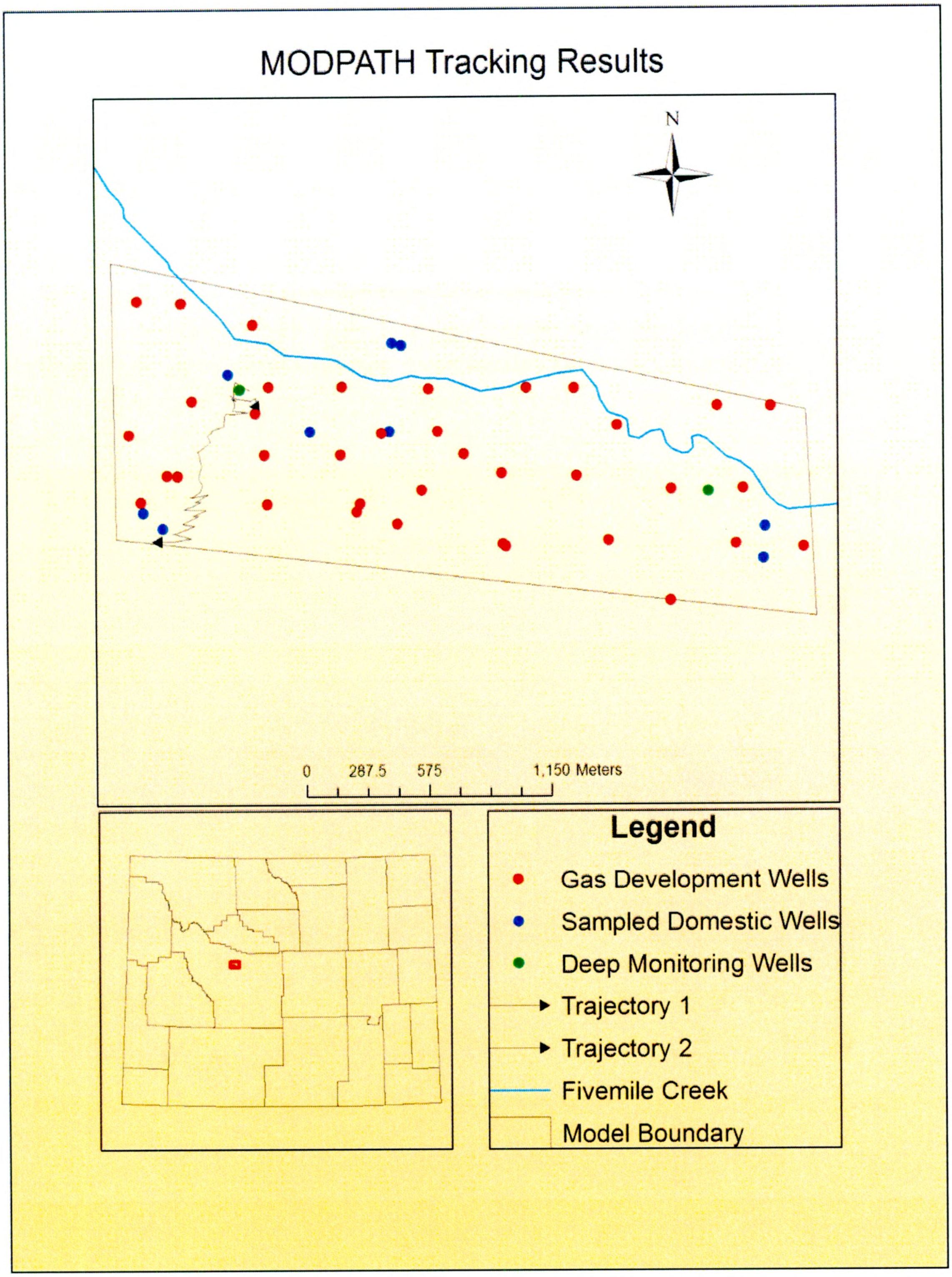


Figure 30: Map of MODPATH particle tracking results. The trajectories show that contaminants found beneath the EPA monitoring well could have originated from a gas development well to the southeast or from areas further southwest.

In order to further illustrate the effects of hydraulic fracturing on groundwater flow systems, pre- and post-fracturing models were compared, as shown in Figures 31, 32, and 33. It is obvious that groundwater flow systems are extremely sensitive to this process, which reinforces the analysis outlined previously describing how injection and extraction patterns can produce pathways that lead to MW01. As in the previous figures, green points represent methane located at MW01, while red points represent starting locations predicted by the model.

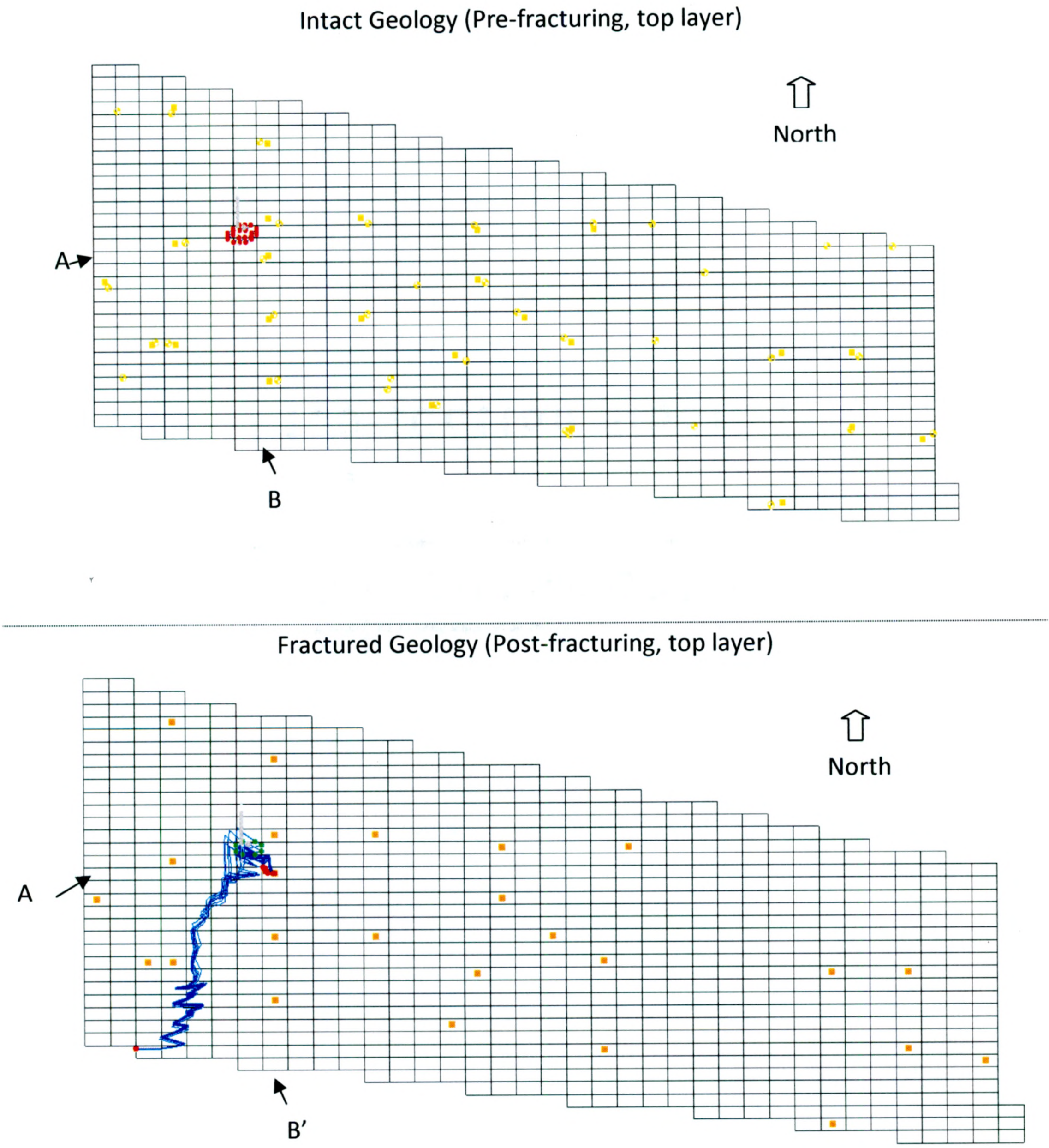
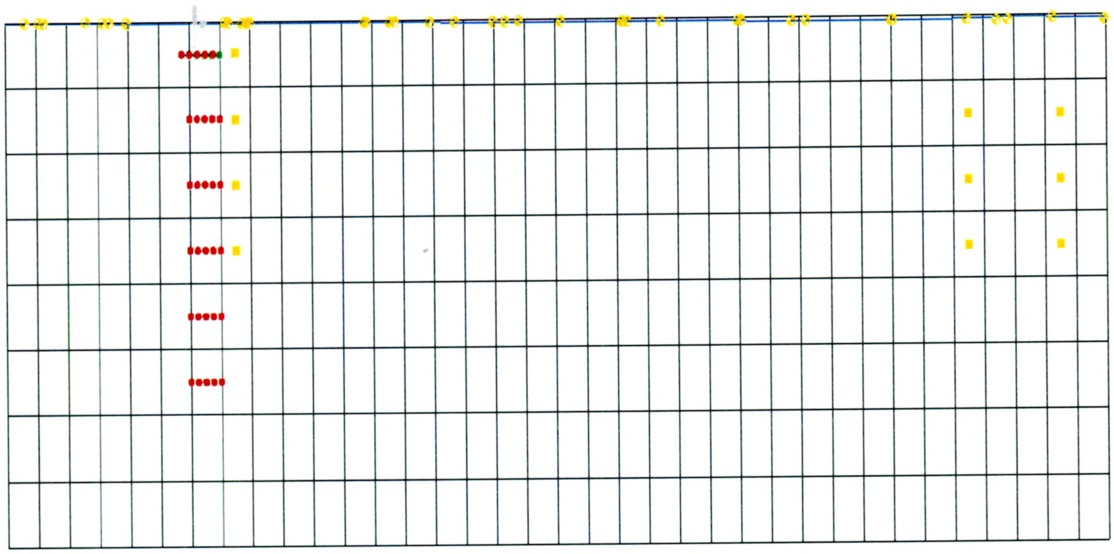


Figure 31: Comparison of the effects of hydraulic fracturing on methane transport. Red points represent the predicted origins of methane found at MW01, which is represented by green points. Yellow squares indicate natural gas wells.

Intact Geology (Pre-fracturing, Row 17, A)



Fractured Geology (Post-fracturing, Row 17, A')

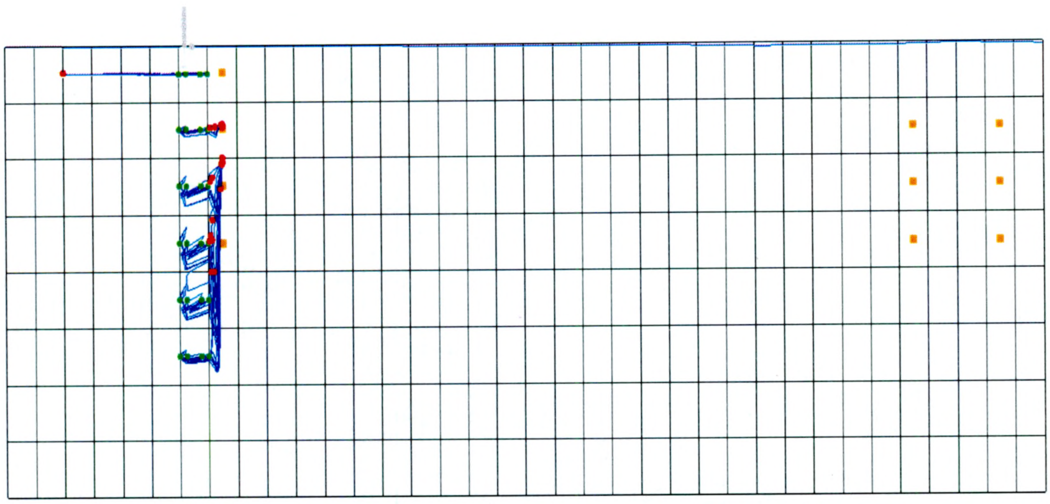
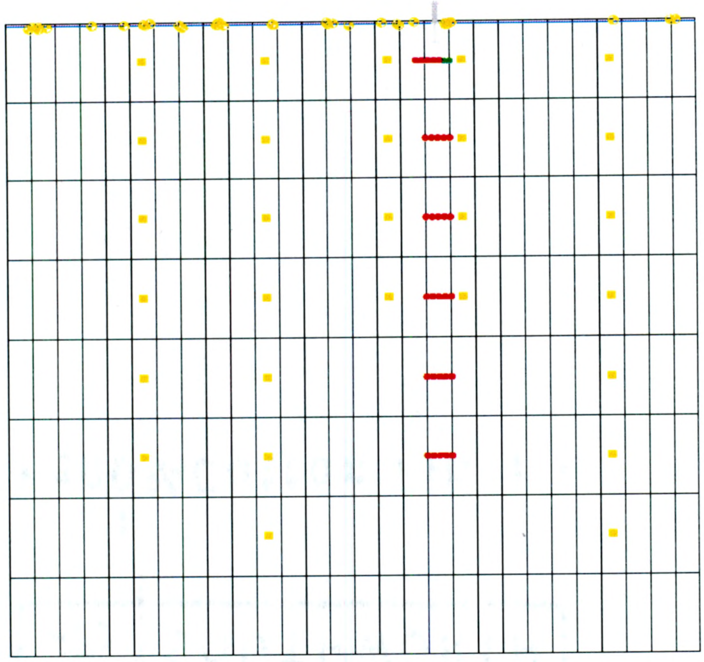


Figure 32: Comparison of effects of hydraulic fracturing on methane transport, row view. Red points represent the predicted origins of methane found at MW01, which is represented by green points. Yellow squares indicate natural gas wells.

Intact Geology (Pre-fracturing, Column 10, B)



Fractured Geology (Post-fracturing, Column 10, B')

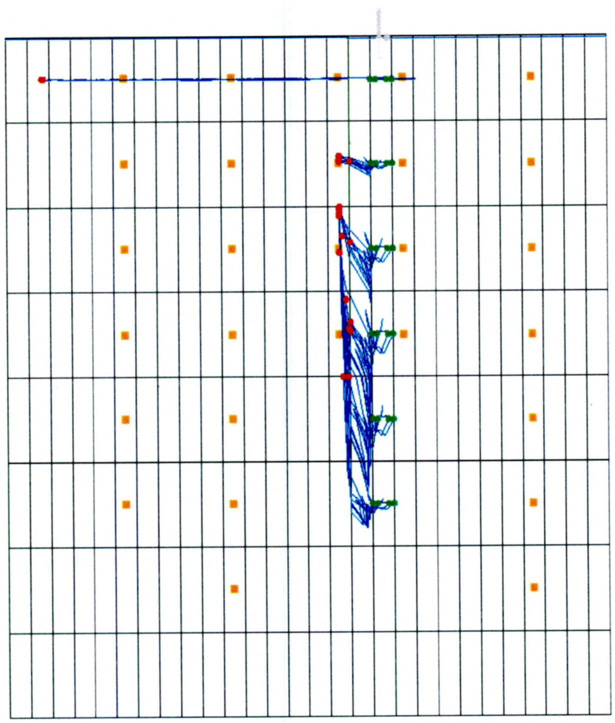


Figure 33: Comparison of effects of hydraulic fracturing on methane transport, column view. Red points represent the predicted origins of methane found at MW01, which is represented by green points. Yellow squares indicate natural gas wells.

6.0 Discussion

6.1 *Assumptions and Justifications*

The resulting numerical models outlining groundwater flow and advective transport simulate groundwater movement and potential pathways through which contaminants could travel through the geology beneath the selected EPA study area under the specified parameters obtained through background research. The models make various assumptions and interpolations from available datasets, each of which can be sources of inaccuracy in the model's results.

The assumption of 50% sandstone and 50% shale conditions extend to the bottom of the models. This is because specific stratigraphy is not detailed from well reports from the WOGCC—only formations and sections of them are identified by letters—and well gamma ray logs are beyond the scope of this study, although they can be used in future research.

It is assumed that there are no confining units in between the Wind River Formation and Fort Union Formation in both models. This is because there were no other formations reported in well stratigraphy, although generalized stratigraphy graphs have suggested that the Indian Meadows Formation and Willwood Formation may act as a leaky confining layer separating the Wind River and Fort Union Formations (Stacy & Lidstone, 2003). The presence of confining layers in between the Wind River and Fort Union formations would affect the outcomes of the model.

Well production values were assumed to be correctly recorded. Due to lack of data, it was assumed that groundwater volume was equivalent to liquefied natural gas volume. This could change the pumping rate in terms of volume per unit time, which could in turn have an effect on the calculated groundwater flow systems. Furthermore, it was assumed that the surface well casings were intact and prevented methane leakage from natural gas wells.

In the second transient model, it is assumed that the change in hydraulic conductivity of shale is equal to the change in 50% shale and 50% sandstone because the increase of sandstone could not be found in the background research. This results in a conservative estimate, since shale has lower hydraulic conductivity values than sandstone.

Injection rates were assumed and inferred for months listed as zero natural gas production. More detailed and clearer records indicating the dates when these wells were hydraulically fractured and volume of fluid injected per day would be useful in strengthening the transient model's results.

It was assumed that the Wind River Formation reaches the surface of the entire model. Adding layers above the Wind River Formation to represent reported alluvial deposits may also have an effect on groundwater flow patterns. More detailed stratigraphic reports would need to be created with specific geological and hydrogeological parameters at specific depths in order to account for the complex geology of the area.

Furthermore, there is the assumption that vertical hydraulic conductivity changes equally throughout the model. This is probably not realistic due to the complex geology beneath the study area. Hydraulic fracturing may stimulate present or create new vertical pathways within the geological formations, which would in turn unevenly increase vertical hydraulic conductivity in the transient model. Due to lack of reported data, it was assumed that increases in horizontal and vertical conductivity were proportional across each layer.

No impervious surfaces and/or human development on land such as roads were entered into the models. Presence of these would create no-flow boundaries on the ground surface that may affect groundwater flow patterns near the surface. However, since casing was being simulated in the model, most of the groundwater flow closer than 1000 feet to the surface was highly constrained.

The MODPATH analysis assumed that the hydraulic fracturing of wells began in January of 1981 before reported gas development and when well production rates were listed as zero cubic feet per day.

6.2 *Sensitivity Analysis and Steady State Model Analysis*

The steady-state model is a preliminary result used as an accuracy assessment in order to validate that the model's results are realistic. The calibrated model's results fell within reported ranges of groundwater recharge rates, showing that the model can be trusted to give accurate measurements on how gas production would affect groundwater flow patterns. Furthermore, the mapping of the steady-state model's results shown in Figure 8 shows that the results are intuitive; the natural groundwater flow patterns move generally from high elevations that are recharge zones to Fivemile Creek, which is a discharge zone. Since the calibrated steady-state model reflects

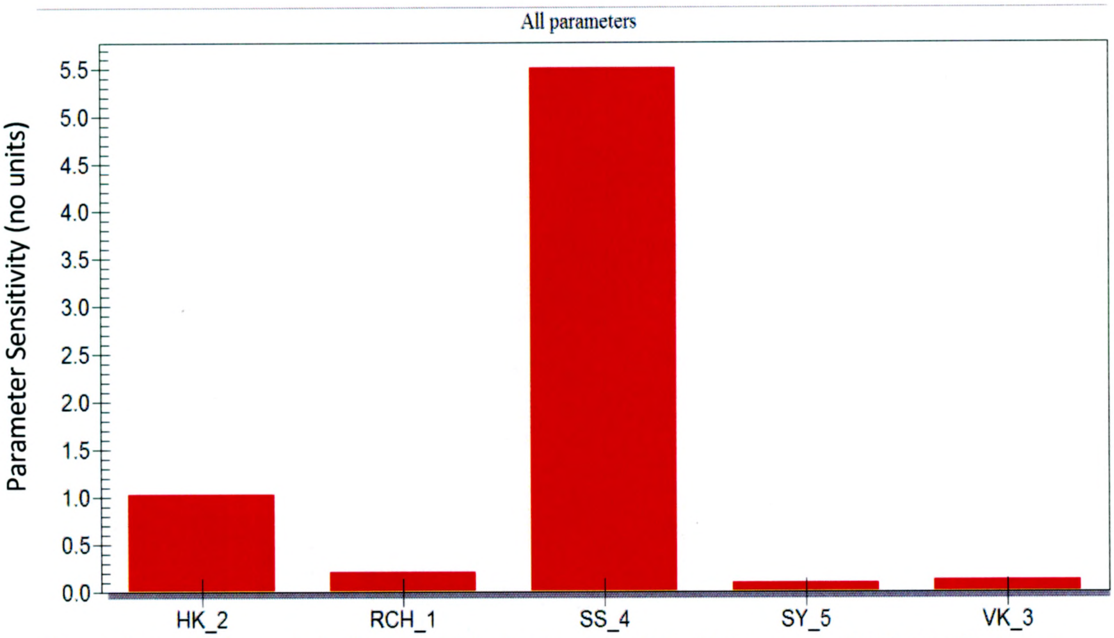


Figure 34: Sensitivity analysis of horizontal hydraulic conductivity (HK), recharge (RCH), specific storage (SS), specific yield (SY), and vertical hydraulic conductivity (VK). Specific storage and horizontal hydraulic conductivity were sensitive in the model, while the other parameters were not.

natural conditions, it can be used to create a transient model showing the gas development wells' effects on the groundwater flow system.

As mentioned in the observed head parameter, there was little observational data to compare calculated head to. As a result, the sensitivity analysis of this model, shown in Figure 34, should be interpreted with caution. In light of this, multiple runs of the transient model have shown that recharge rate, specific yield, and vertical hydraulic conductivity are insensitive in this model. Horizontal hydraulic conductivity and specific storage are sensitive in this model, so caution must be used when making assumptions for these values. In other words, changing the values for specific storage and horizontal hydraulic conductivity changed the calculated head values that were being compared to the observed head values, while changing recharge, specific yield, and vertical hydraulic conductivity had little to no effect. Realistic values that can be supported through previous research and/or observational studies should be used in order to reduce the uncertainty of the model.

The sensitivity analysis takes initial values of specific storage and horizontal hydraulic conductivity (the two sensitive variables) and runs the model multiple times to find values that minimize the error (i.e., are a better match) between calculated and observed head values (Wright et al, 2012). These new values for specific storage and horizontal hydraulic conductivity that resulted in head values that were closer to the observed head values—which results in a lower percent error—are referred to as "calibrated values". Figure 35 shows how the calibrated values resulted in a more accurate model than the initial values.

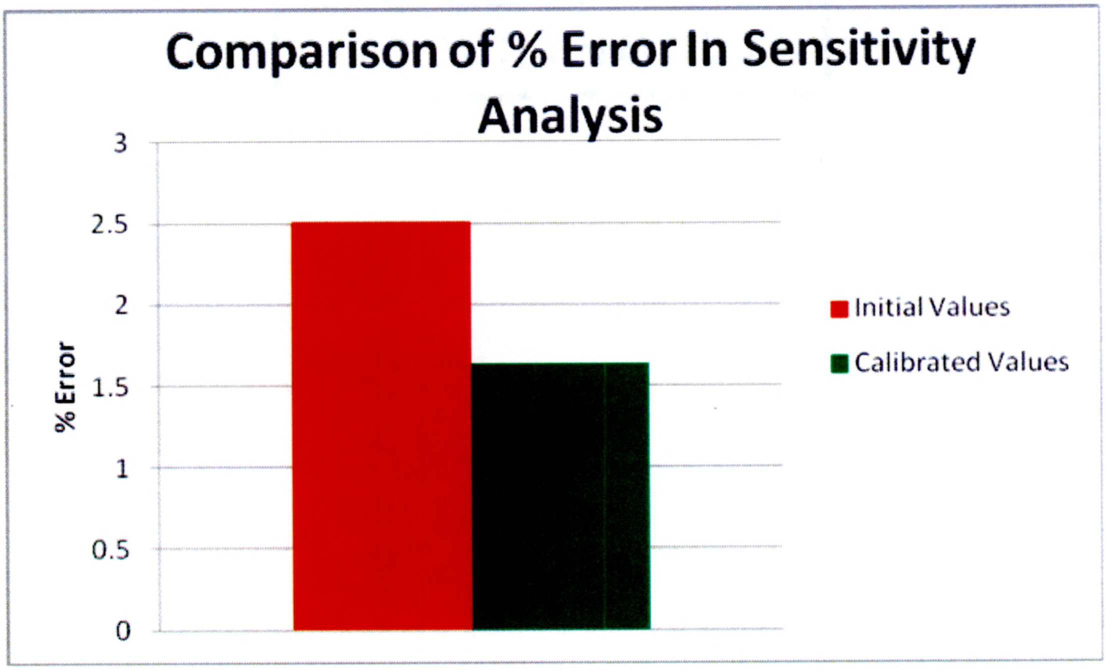


Figure 35: A quantitative measurement illustrating how the sensitivity analysis reduced head discrepancy (error). The initial values (red column) had a higher % error than the calibrated values (green column) that were the result of the sensitivity analysis.

6.2.1 Sensitivity Models

6.2.1.1 Altered Specific Storage

In order to illustrate the effects of the sensitive variables (specific storage and horizontal hydraulic conductivity), a value of 0.001 ft^{-1} was set for specific storage while the other parameters were left at their calibrated values. The last stress period of the model with a specific storage of 0.001 ft^{-1} is shown in Figures 36, 37, and 38.

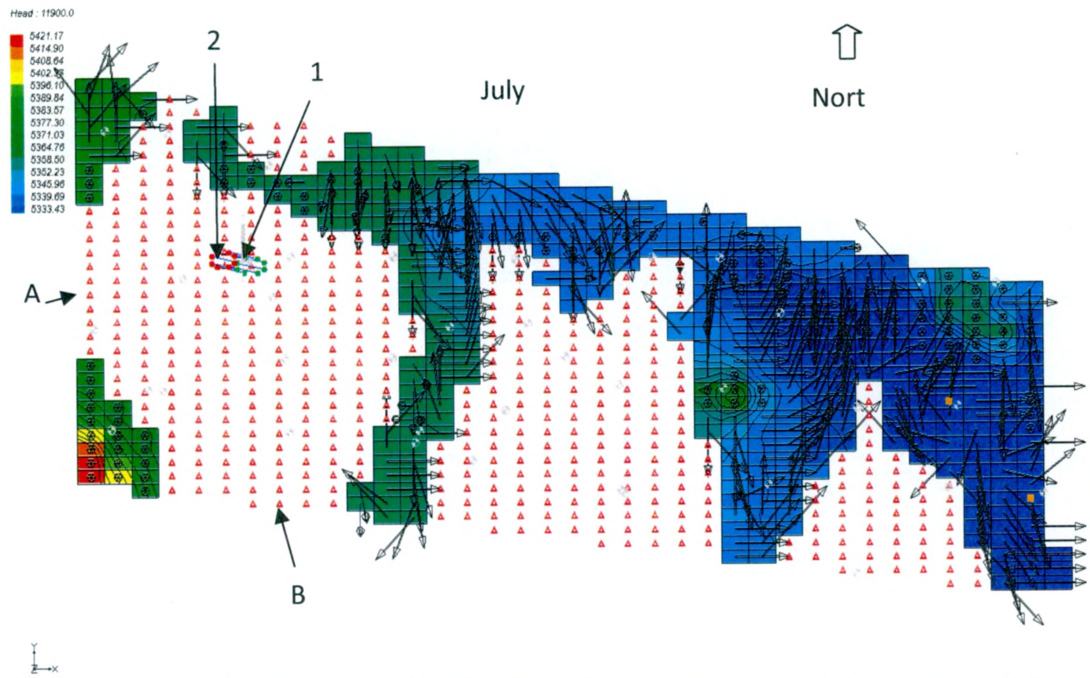


Figure 36: The last time step of the transient model including gas development wells with a specific storage value of 0.001 ft^{-1}. The EPA monitoring well is outlined in black, which is the starting location of the MODPATH particles in green, labeled as 1. The ending locations of the MODPATH particles are red and labeled as 2.

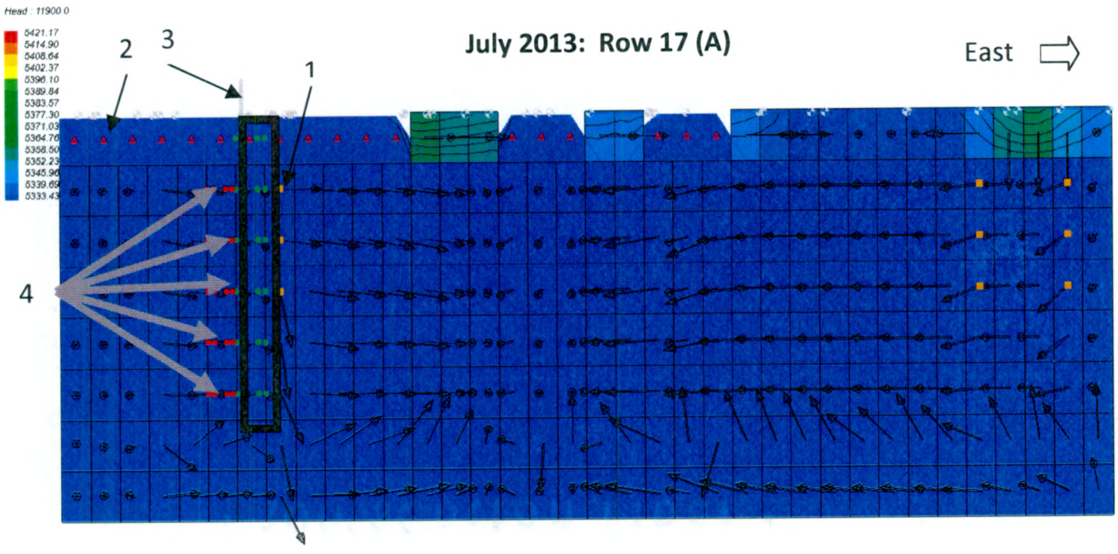


Figure 37: The row view of the model shown in Figure 32. MODPATH trajectories, labeled as 4, do not trace back to the gas development well labeled as 1 from MW01 labeled as 3 and outlined in black as opposed to previous models. Furthermore, dry cells such as the one labeled 2 are much more prevalent, showing that this model is very sensitive to specific storage values.

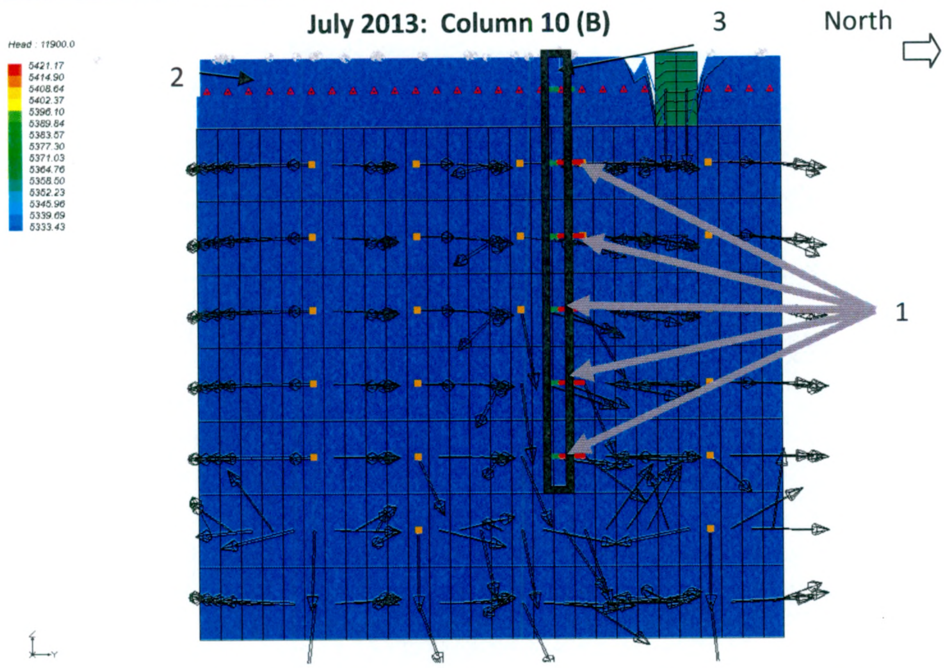


Figure 38: This column view shows how the MODPATH trajectories, labeled as 1, are now horizontal in flow instead of showing vertical transport. Furthermore, most of the top layer is dry, with an example dry cell labeled as 2. The green points represent the starting location of MW01, labeled as 3 and outlined in black, while the red locations represent potential starting locations.

These three figures illustrate that the model is extremely sensitive to specific storage. Not only do a majority of the top layer's cells run dry, but the groundwater flow systems also change dramatically. This is illustrated by both the vectors representing the groundwater flow systems and the MODPATH particles labeled as 1 that now show negligible vertical travel in Figures 37 and 38. Furthermore, these particles do not trace back to a gas development well as can be seen in Figure 36, where 1 indicates MW01 as the starting location of the anthropogenic methane in groundwater. The red circles labeled as 2 are the calculated origins of these particles under a specific storage of 0.001 ft^{-1}.

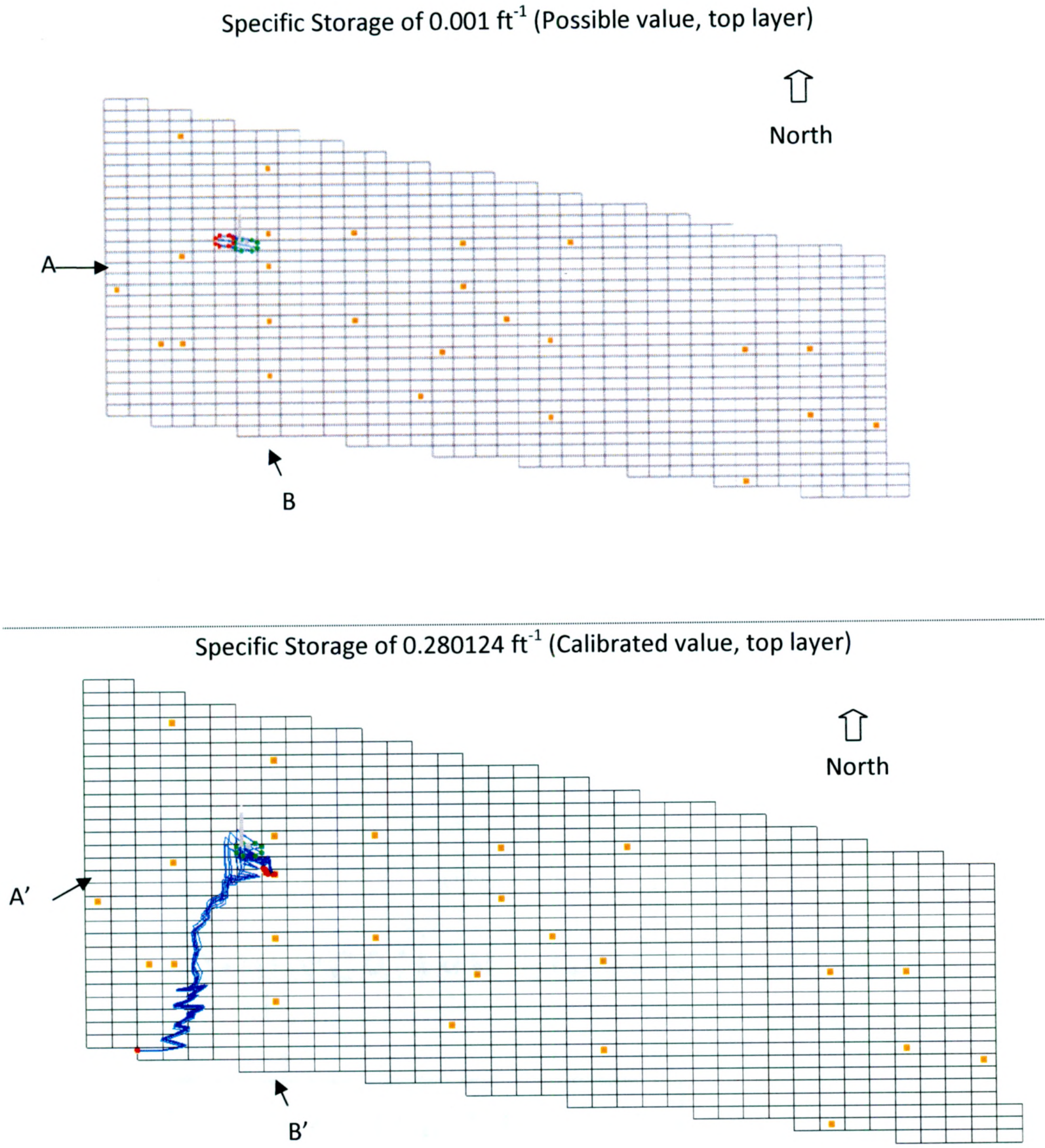
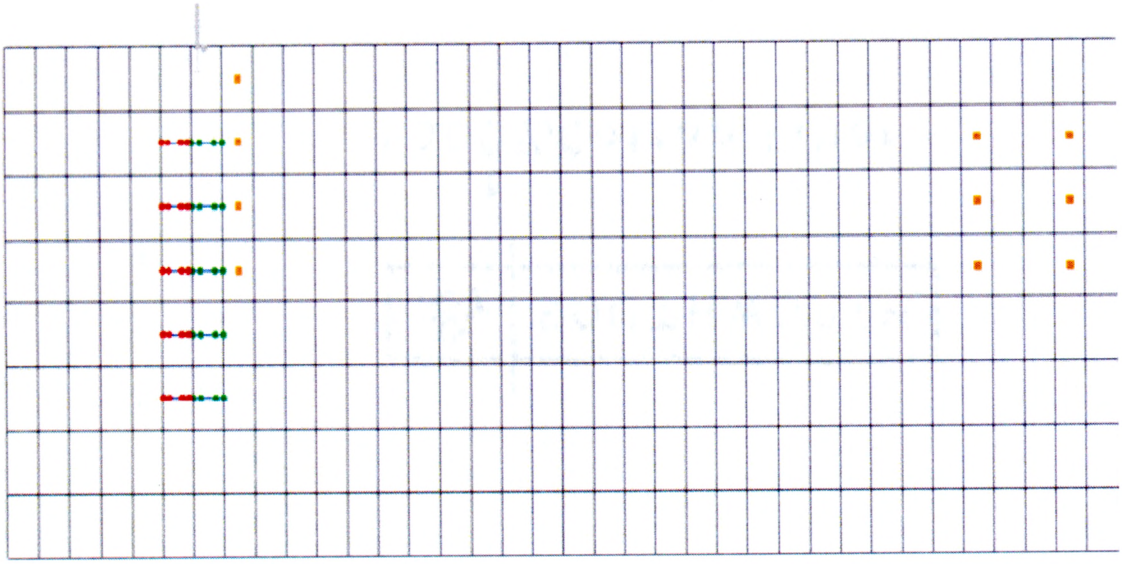


Figure 39: Comparison of the effects of different specific storage values on methane transport, top view. Red points represent the predicted origins of methane found at MW01, which are represented by green points. Yellow squares indicate natural gas wells.

Specific Storage of 0.001 ft^{-1} (Possible value, Row 17, A) East



Specific Storage of 0.280124 ft^{-1} (Calibrated value, Row 17, A') East

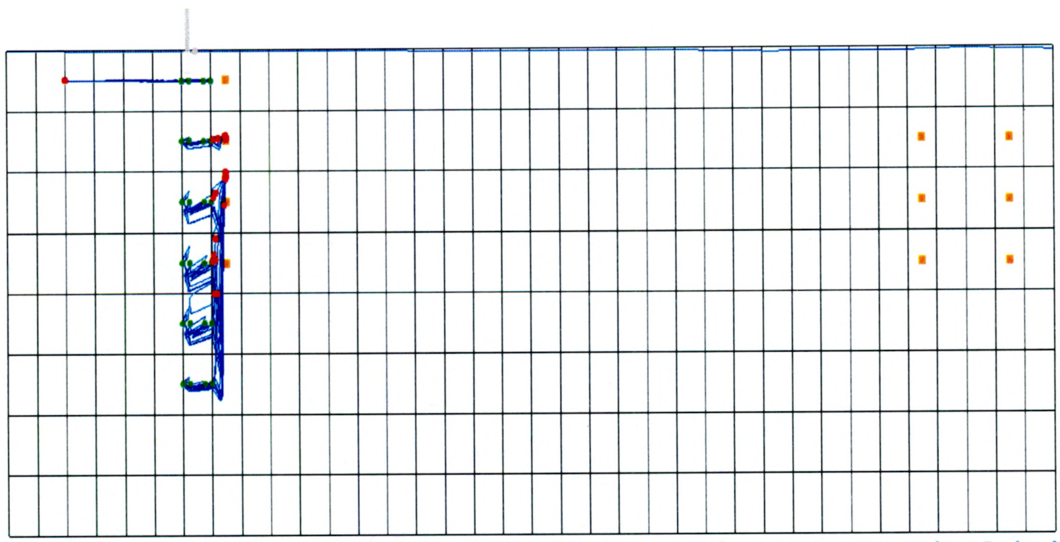
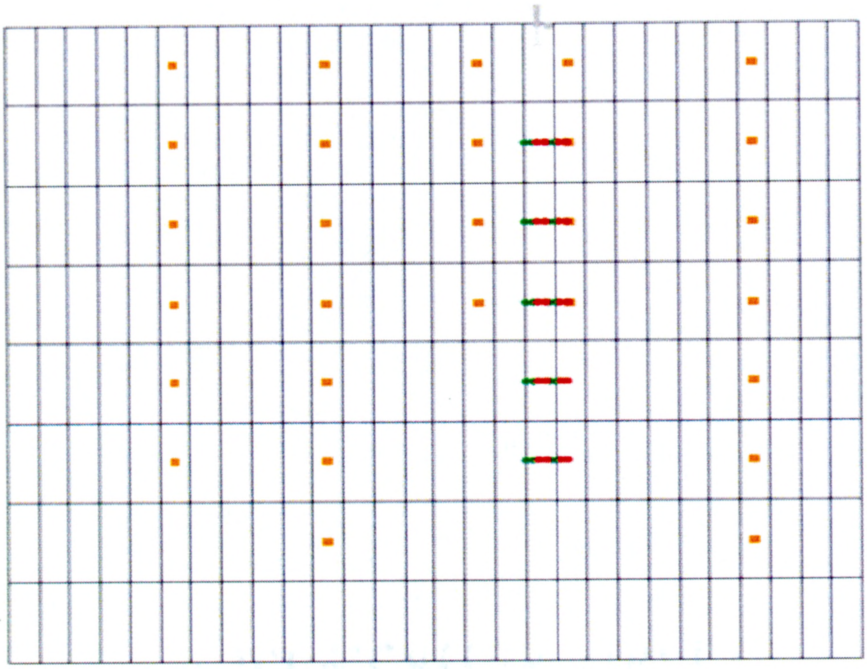


Figure 40: Comparison of effects of different specific storage values on methane transport, row view. Red points represent the predicted origins of methane found at MW01, which are represented by green points. Yellow squares indicate natural gas wells.

Specific Storage of 0.001 ft^{-1} (Possible value, column 10, B) North



Specific Storage of 0.280124 ft^{-1} (Calibrated value, column 10, B')

North

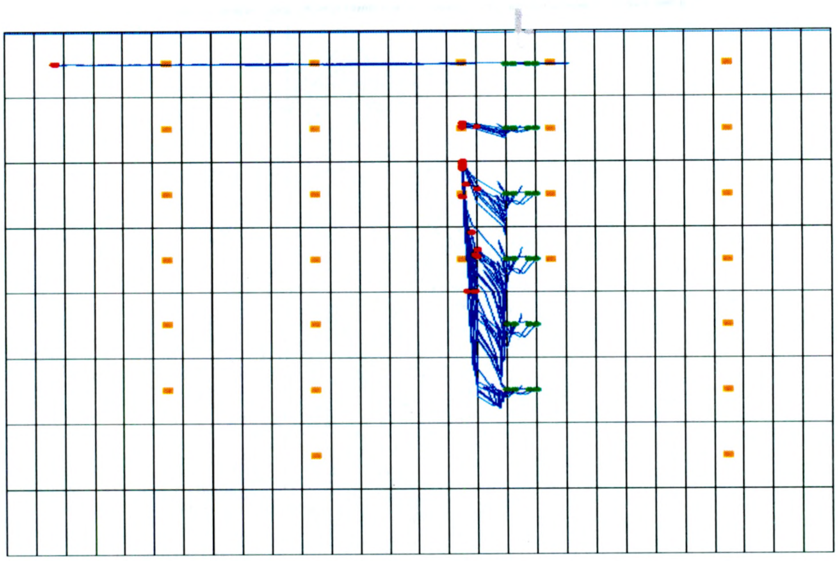


Figure 41: Comparison of effects of specific storage values on methane transport, column view. Red points represent the predicted origins of methane found at MW01, which are represented by green points. Yellow squares indicate natural gas wells.

Figures 39, 40, and 41 directly compare the two MODPATH simulations representing the possible and calibrated specific storage values. Since specific storage is the most sensitive variable, it is not surprising that a change in the value has profound effects on the MODPATH trajectories, which include the loss of vertical particle movement, excessive cell drying, and different calculated starting locations.

6.2.1.2 Altered Horizontal Hydraulic Conductivity

In order to illustrate the moderate sensitivity of horizontal hydraulic conductivity, the fractured horizontal hydraulic conductivity was increased to 200 feet per day as opposed to the calibrated value of approximately 141.874 feet per day. The resulting models illustrate the final time step in July 2013 and are shown in Figures 42, 43, and 44.

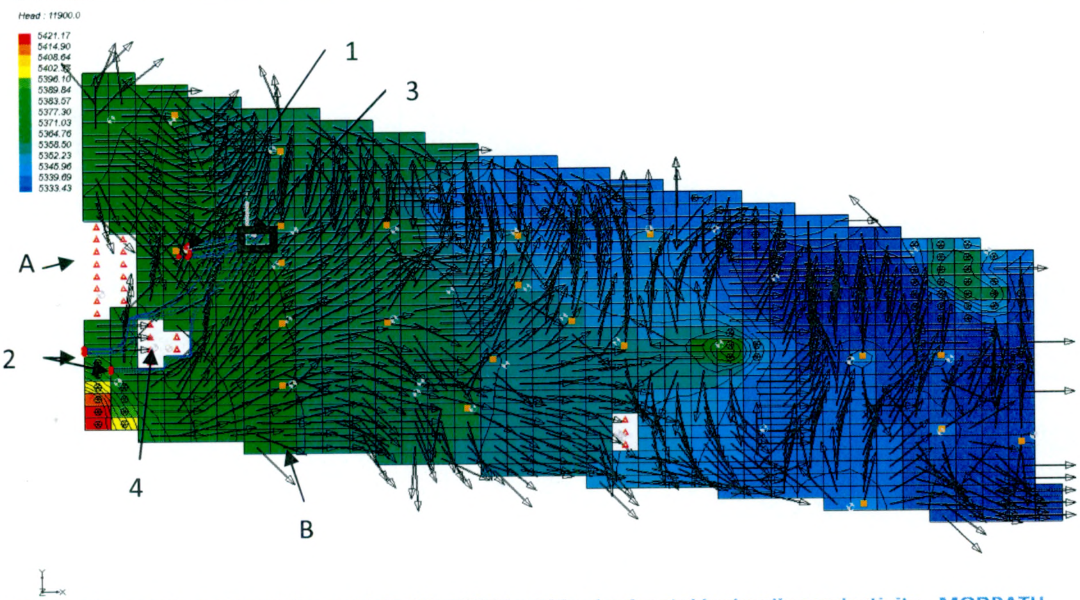


Figure 42: The last time step of the model with a 200 feet/day horizontal hydraulic conductivity. MODPATH particles trace back from MW01, outlined and labeled as 3, to a well labeled as 1 in deep systems or the points labeled as 2 through shallow systems.

It can be seen in Figure 42 that although there is not as much cell drying as compared to the change in specific storage, the flow systems are shown to be less sensitive to well activity when there is a higher horizontal hydraulic conductivity value. As a result, the MODPATH particles representing methane originating from MW01, which is outlined and labeled as 3, are traced back to a southwestern locations labeled as 2 and a different gas development well than the calibrated model predicted. This other well is labeled as 1, and like the original transient model showing the effects of gas development wells, the deeper flow systems carry the MODPATH particles in system 1 and the shallower systems carry the particles labeled as 2. The dry cells labeled as 4 could have also impacted the direction of flow systems, which may have been traced back to the wells there.

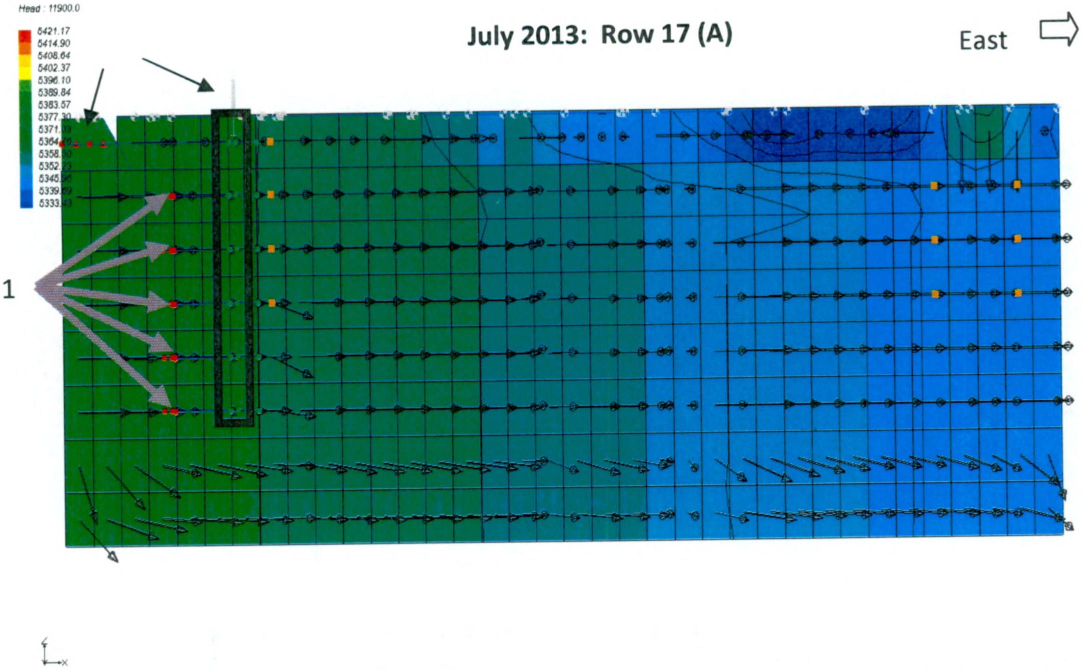


Figure 43: A cross section of the view shown in Figure 35. MW01, which is outlined and labeled 3, is the starting point of MODPATH particles, which end at the red points labeled 1. Dry cells are labeled as 2, which may have affected flow patterns.

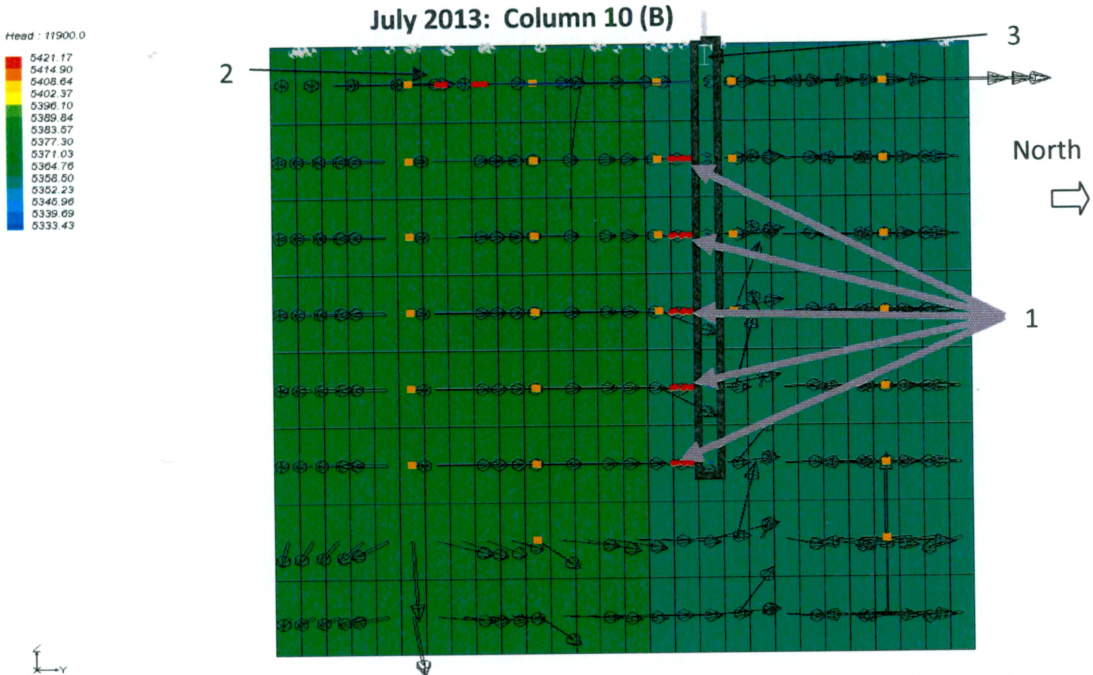


Figure 44: A cross section of the top view shown in Figure 35. MW01, which is outlined and labeled 3, is the starting point of MODPATH particles. Deep flow systems brought MODPATH particles to the red points labeled 1, while shallow flow systems brought particles to the red points labeled 2.

Although the deeper flow systems, labeled as 1 in Figure 43, approximately imitate the trajectories of the calibrated model, the vertical movement in the calibrated model was lost similarly to when the specific storage was altered. This is shown in Figures 43 and 44 by the trajectories labeled as 1 where vertical transport is negligible when comparing the trajectories to the starting points in MW01, which is outlined and labeled as 3 in both figures. Shallower flow systems in Figure 44 are labeled as 2 and follow more natural conditions, although they are impacted by the dry cells labeled as 2 in Figure 43. These dry cells also impacted the MODPATH trajectories more noticeably than in the calibrated model.

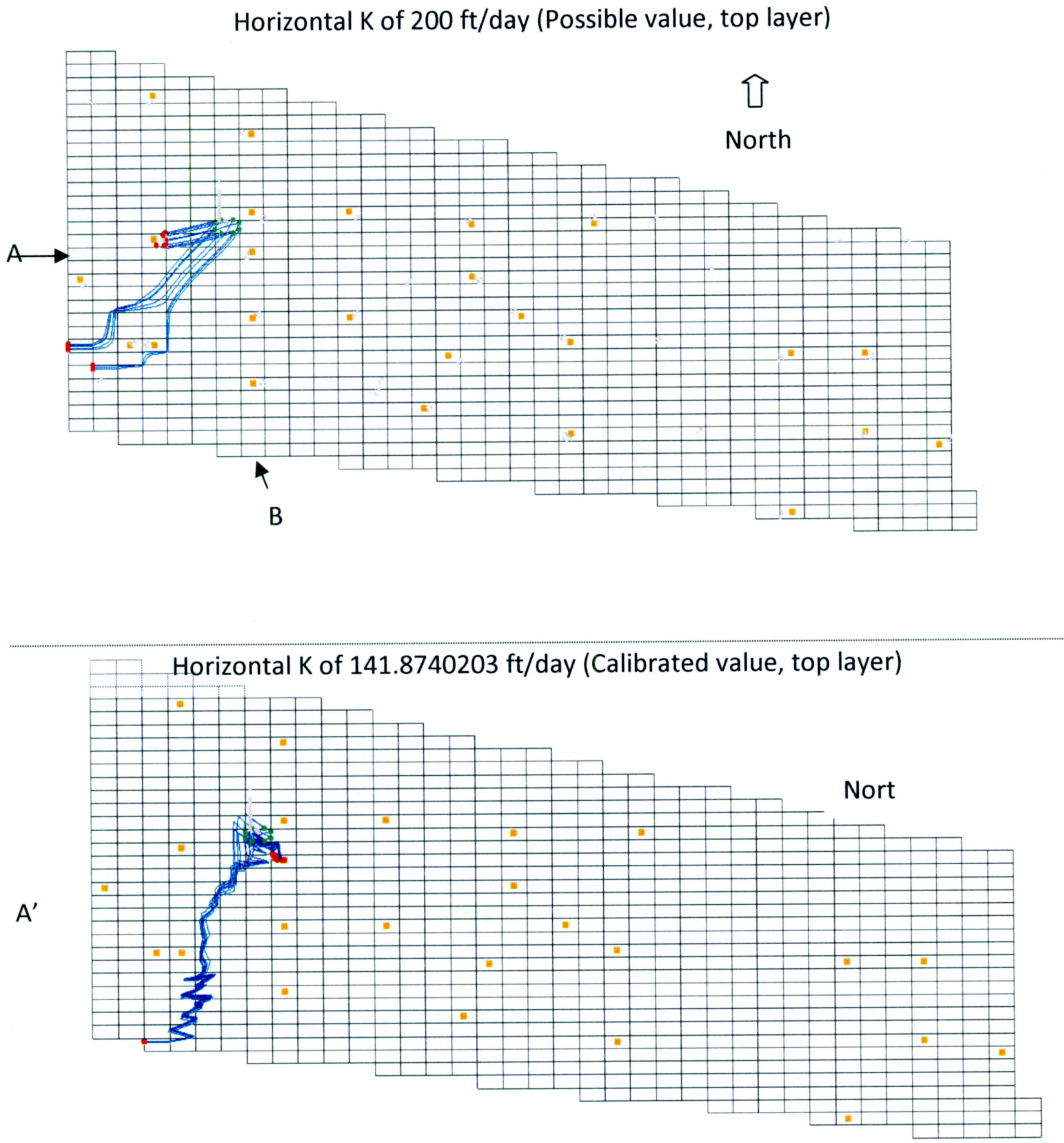


Figure 45: Comparison of the effects of different horizontal hydraulic conductivity values on methane transport, top view. Red points represent the predicted origins of methane found at MW01, which are represented by green points. Yellow squares indicate natural gas wells.

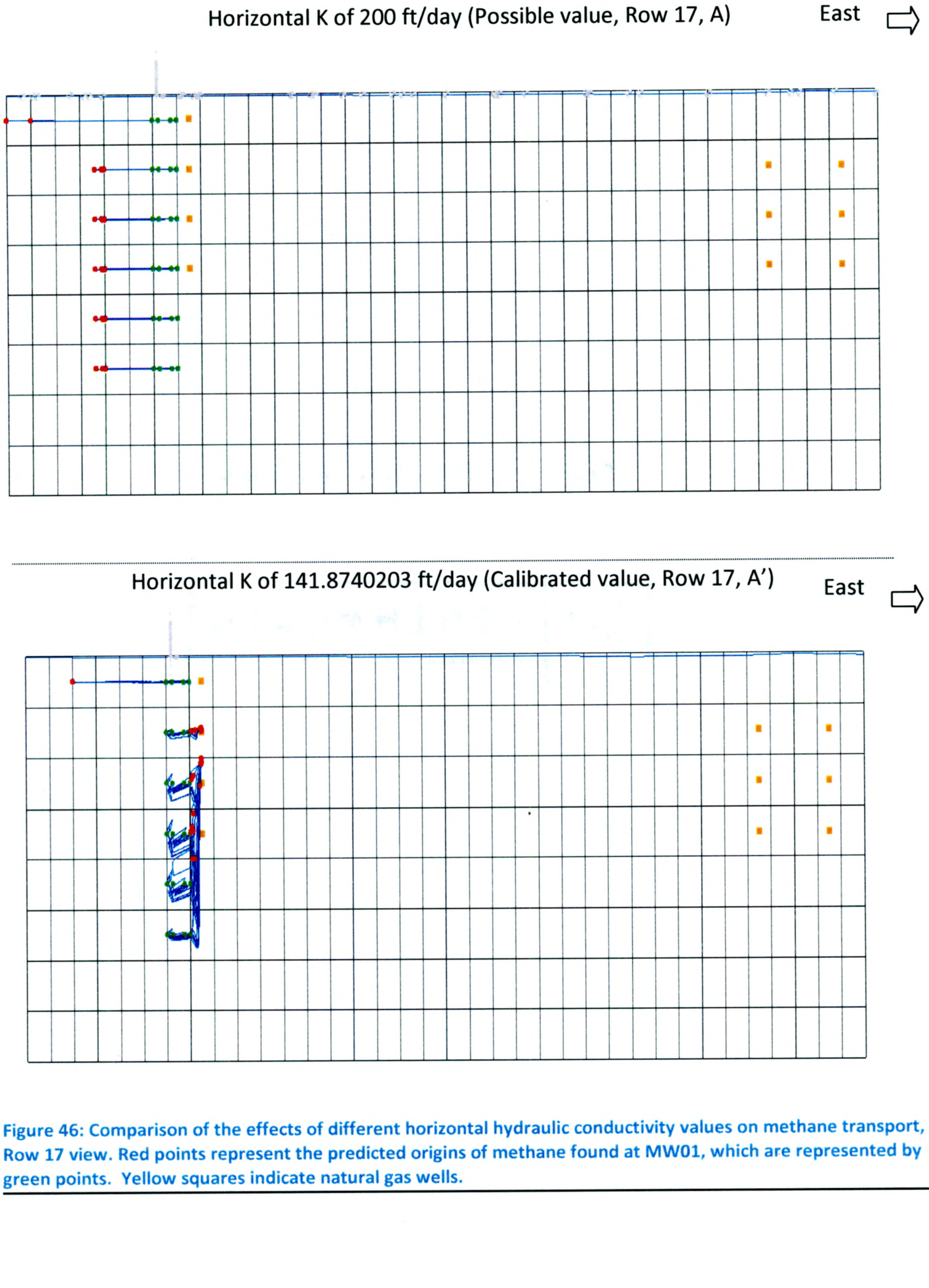
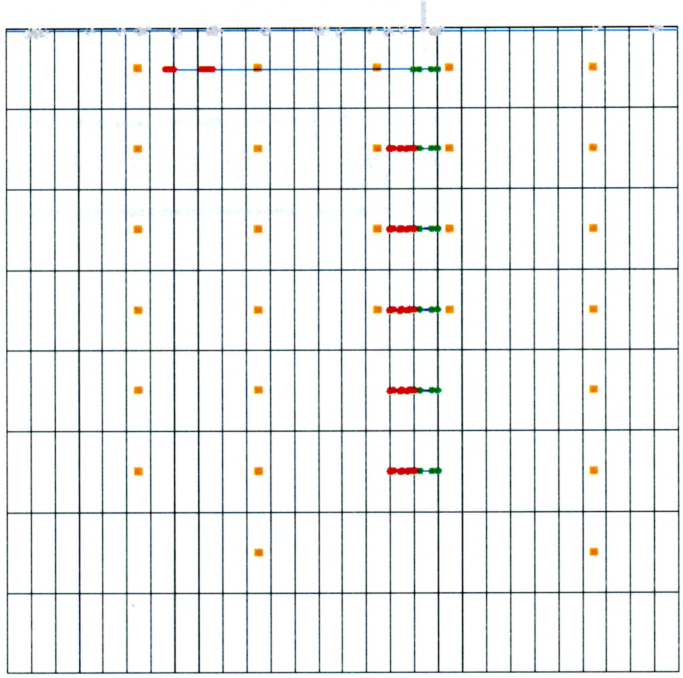


Figure 46: Comparison of the effects of different horizontal hydraulic conductivity values on methane transport, Row 17 view. Red points represent the predicted origins of methane found at MW01, which are represented by green points. Yellow squares indicate natural gas wells.

Horizontal K of 200 ft/day (Possible value, Column 10, B) North



Horizontal K of 141.8740203 ft/day (Calibrated value, Column 10, B')

North

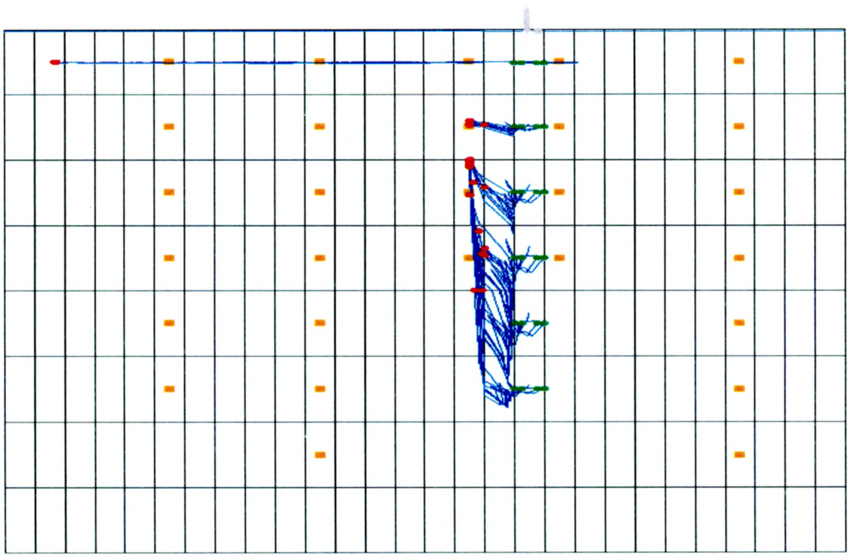


Figure 47: Comparison of the effects of different horizontal hydraulic conductivity values on methane transport, Column 10 view. Red points represent the predicted origins of methane found at MW01, which are represented by green points. Yellow squares indicate natural gas wells.

Figures 45, 46, and 47 further illustrate the moderate sensitivity of horizontal hydraulic conductivity. Since this parameter is not as sensitive as specific storage, the model has not changed as drastically when compared to its altered specific storage counterpart. However, as mentioned previously, the vertical movement of the MODPATH trajectories has been lost when compared to the optimal value that was used and different starting points (red dots in the figures) were calculated than those in the calibrated model.

6.3 *MODPATH Analysis*

The particle set generated by MODPATH in the optimal model includes data that illustrates longitude, latitude, and elevation of the particles at each time step beginning on January 1, 1981 and ending on August 1, 2013. It is important to note that it was not possible for MODPATH particles to be generated at a specified depth; the particles were generated in the middle of the cell surfaces that were beneath the EPA monitoring well, which had reported contamination at 239 meters (about 784 feet) below the ground surface (Digiulio et al., 2011), which is an elevation of 1,396 meters (about 4,583 feet). Although the depth of originating points at the gas development wells were determined by MODPATH, there were no records of the depths at which hydraulic fracturing occurred from the data obtained regarding the gas development wells. The starting points at the well had a wide range of elevations, with the deepest being at about 731 meters and the shallowest being at about 1,215 meters. It would be beneficial to investigate whether hydraulic fracturing occurred at these elevations on this well indicated by MODPATH.

The top layer MODPATH particles traveled southwest along the steady state vectors, which illustrates the effect of proper casing. However, it is possible that the calculated trajectory is influenced by dry cells preventing groundwater flow near producing gas wells in the southwestern section of the model. If proper parameter values could be measured and modeled to prevent cell drying, it may have been possible that the contaminants originated from these cells that contain natural gas wells.

The MODFLOW packages employed in the version of GMS (v7.1) used in this thesis are made to simulate wells rather than natural and anthropogenic vertical fractures in the lithology of the system, which could be other pathways for vertical transport (Myers, 2012). However, this model only showed vertical travel in gas development wells during the MODPATH analysis when there could have been other vertical pathways present and/or created during the hydraulic fracturing process (Rozell & Reaven, 2012). With this in mind, the MODPATH trajectories are not necessarily inaccurate, but rather that they are too simplistic. Data pertaining to location, hydrogeology, and dimensions of existing and anthropogenic fractures in the geology would have to be collected and modeled with other modeling techniques such as the MT3D module. MT3D analyzes MODFLOW solutions to simulate solute transport (methane in groundwater in this case) in order to create more detailed simulations of how methane can move through the groundwater flow systems if it exsolves from the groundwater as opposed to MODPATH, which assumes the methane is always dissolved in the groundwater.

Although there are vertical discrepancies, the fact that the transient model can trace contaminants from beneath MW01 to gas development wells supports the EPA's conclusion that hydraulic fracturing was the most likely cause of groundwater contamination in the local drinking water wells within the study area. The discrepancy could be due to inaccurate parameters and the model's limitations on simulating vertical transport.

6.4 *Challenges*

There were many challenges that were encountered during the data collection, organization, model creation, and model analysis phases of this thesis. They mainly stem from lack of complete data, which in turn leads to assumptions that can affect the resulting model's reliability. Estimating values for parameters such as specific yield and specific storage after hydraulic fracturing occurred was especially difficult and is the most likely source of error in the models.

The datasets obtained from the WOGCC were inconsistent, poorly organized and sometimes did not label the units in the dataset. For example, geological tops and well depths did not have units associated with the reported numbers (See Appendix B). While the website has large amounts of data, the format it is presented in is very difficult to work with and some links were not working.

Although reports on how hydraulic fracturing affects hydraulic conductivity were found, there was no data available that gave a specific ratio or value for how specific yield and specific storage would change. This was the most difficult challenge to meet in terms of time.

Compared to production history, very little observational data was available (Wright, McMahon, Mueller, & Clark, 2012) for observed-calculated head comparison. This is because the observation wells were constructed during the EPA study and no previous monitoring well data within the model's extent was available before that time on the National Water Information System, which is the USGS database of surface and groundwater wells (United States Geological Survey, N.D.). Furthermore, the USGS website stated on May 22, 2012 that "groundwater-level monitoring at most wells in Wyoming will be discontinued June 30, 2012 due to insufficient funding" (United States Geological Survey, N.D.). This will present challenges for future groundwater projects.

Some datasets were reported in metric and others in imperial units, so these measurements also posed a challenge. However, proper conversion factors were able to compensate for this discrepancy.

6.5 *Future Research*

This thesis can be built upon in a variety of ways in future projects. The Pavillion, Wyoming case study can be improved by creating more K (horizontal) layers in order to get a more accurate calculation of vertical advective transport by generating more MODPATH starting locations in the EPA monitoring well. The grid can also be made to have more cells in order to have a higher resolution-model. This would allow a more accurate representation of the location of the wells during the MODPATH analysis since the model assumes that the well is located in the center of the cell. As mentioned previously, this should be done with more recent versions of GMS equipped with modules made to include vertical pathways other than wells such MT3D to simulate the movement of solutes within the groundwater flow systems. The MT3D tool can be used to simulate methane gas that leaves the groundwater during advective transport, allowing another potential vertical pathway towards the surface. However, data regarding methane concentration within the groundwater is needed, so further data would need to be collected in order to have a proper MT3D analysis.

The model can be improved by creating more K (horizontal) layers in order to get a more accurate calculation of vertical advective transport by generating more MODPATH starting locations in the gas development wells. This should be done with versions of GMS equipped with modules made to include vertical pathways other than wells. Grids with more cells can be used to increase the resolution and in turn the accuracy of the model.

If resources are available, it would also be preferable to obtain geological samples of the study area and determine the different parameters used in the model instead of using ranges of previously reported measurements. Furthermore, the gamma-ray well logs available on the WOGCC database can be tabulated and analyzed to more accurately assess the lithologies at varying depths and calculate more accurate hydraulic conductivity values; shale results in higher gamma readings, while sandstone gives lower emissions (Glover, 2012). A ratio of sandstone to shale can be used to calculate more realistic hydraulic conductivity values rather than assuming 50% sandstone and 50% shale for the entire system.

This model creation methodology is not limited to the Pavillion, Wyoming study; the technique can be used to create groundwater models of any known area, such as the Catskill/Delaware watershed in New York City, where concern regarding water contamination from unconventional natural gas extraction has been prevalent in both the scientific and social communities. More recent versions of GMS should be used in order to perform a more accurate and detailed analysis of groundwater flow trajectories.

Furthermore, this technique can be used in modeling projects other than investigating groundwater contamination from hydraulic fracturing; it can be used to model groundwater flow with regards to any kind of event that can impact groundwater flow systems.

7.0 Conclusion

Groundwater modeling has shown that advective groundwater transport is a possible mechanism through which contaminants from hydraulically fractured wells could reach areas that were reported to be contaminated in the EPA Pavillion, Wyoming case. This supports the EPA's conclusion from a hydrogeological perspective that groundwater contamination originated from hydraulically fractured wells. Although there was a vertical discrepancy that could be due to simplified parameters and assumed values, simulated pathways of advective groundwater transport shows that proper well casing integrity and well location are crucial in minimizing threats to underground sources of drinking water. The MODPATH analysis illustrated that intact surface casing is effective when attempting to minimize impacts on groundwater flow systems, however casing quality can be an issue when wells are stimulated with large volumes of water under high pressure.

The resulting models also showed that the processes of injection and extraction both have significant yet different effects on groundwater flow systems' flow patterns. Although the extent of these effects is difficult to model without proper observational data, it is important to consider the potential consequences that these alterations can have on groundwater resources, especially if the resource in question is an underground source of drinking water like the Wind River formation. If the flow patterns' trajectories are changed considerably, this can have negative side effects on other groundwater uses such as agriculture and drinking water by reducing available supply. It would be beneficial to model the effects of well stimulation via hydraulic fracturing prior to well construction as part of the risk assessment process in order to determine the ideal locations for gas development wells.

This thesis also illustrates how TINs can be used in the GIS-conceptual model approach in GMS 7.1. It was found to be effective in automating the data entry steps of groundwater model creation as opposed to manually entering values in tables. Although TINs have been used previously in GMS procedures regarding subsurface stratigraphy, the specific published tutorials for GMS 7.1 do not involve using TINs in the conceptual model approach. The TINs in this thesis were used to define surface topography and head-stages, which reduces time dedicated to manual data entry.

If resources are available, it would also be preferable to obtain geological samples of the study area and determine the different parameters used in the model instead of using ranges of previously reported measurements. Furthermore, the gamma-ray well logs available on the WOGCC database can be tabulated and analyzed to more accurately assess the lithologies at varying depths and calculate more accurate hydraulic conductivity values; a ratio of sandstone to shale can be used to calculate more realistic hydraulic conductivity values rather than assuming 50% sandstone and 50% shale for the entire system. This data can be used instead of assumed values in order to further support the model's credibility.

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9.0 Appendices

9.1 Appendix A

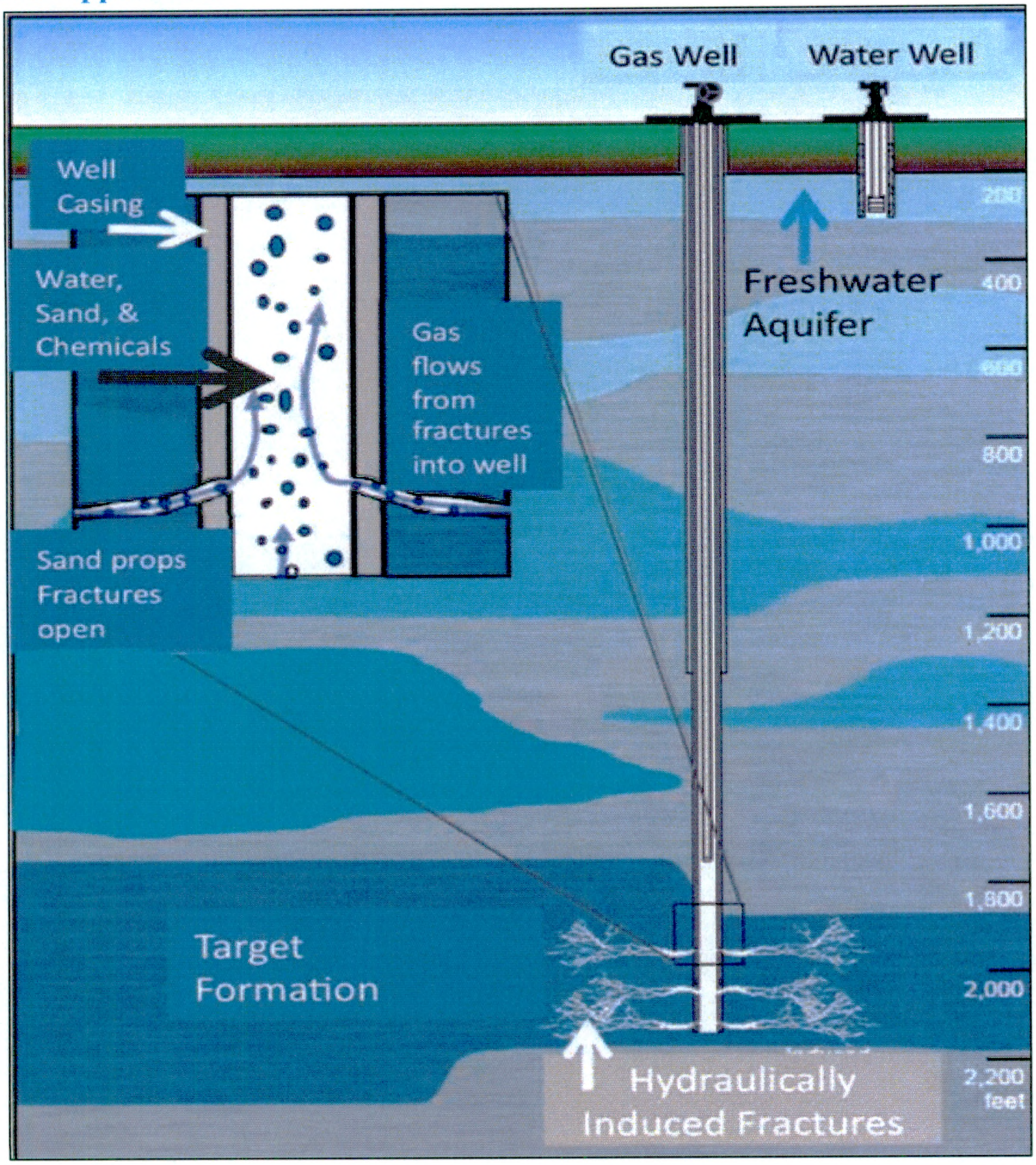

Figure A1: A diagram outlining the hydraulic fracturing process. In theory, a well is cased when it is in contact with freshwater aquifers that act as underground sources of drinking water. Fluid containing water, sand, and chemicals is injected into the well at high pressure to depths containing natural gas deposits in order to extract gas from the formation into the borehole to be brought to the surface (Source: http://www.kgs.ku.edu/Publications/PIC/pic32.html Accessed December 9, 2013).

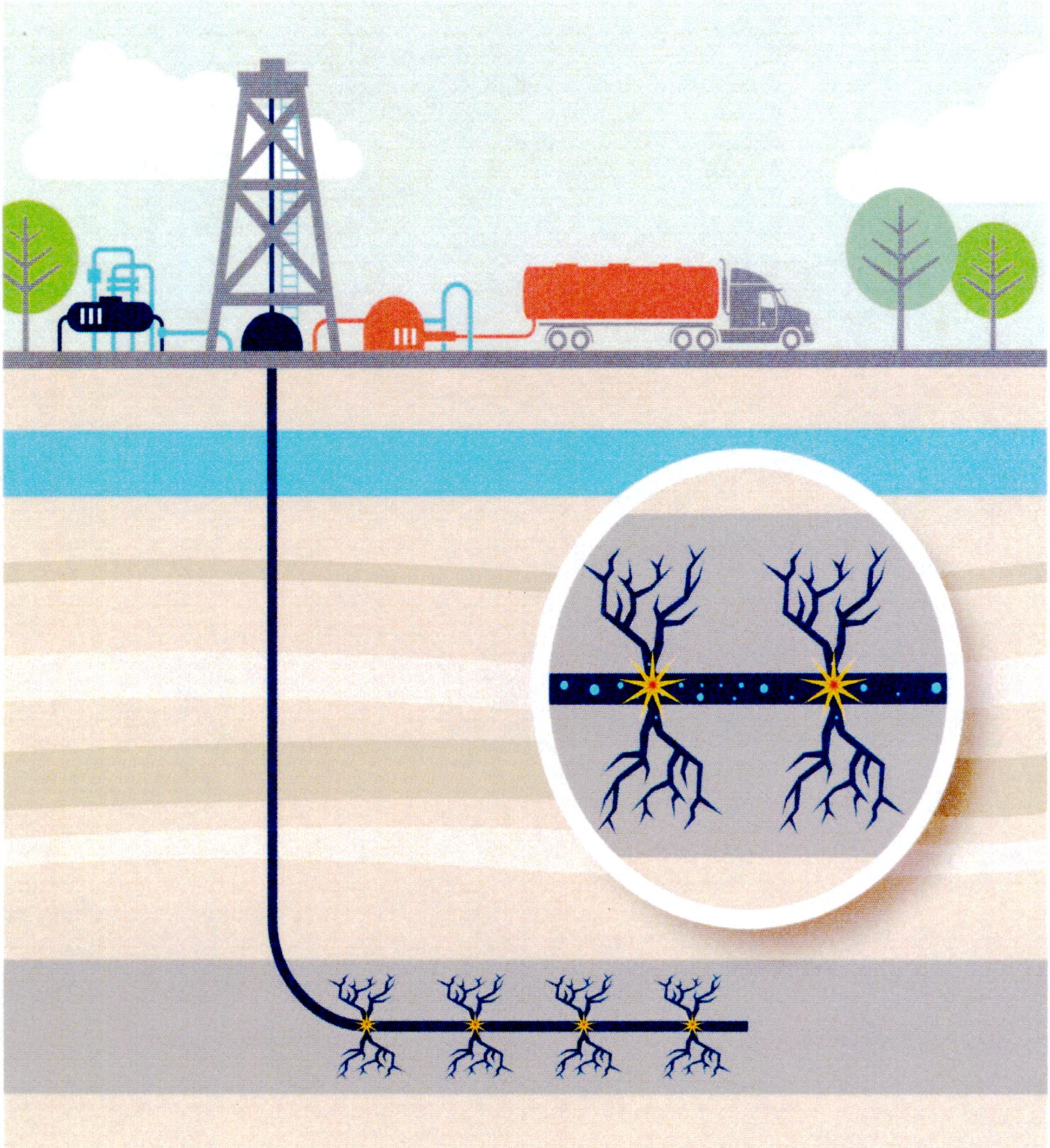

Figure A2: A horizontal well undergoing the hydraulic fracturing process outlined in Figure A1. The combination of these two techniques (horizontal drilling and hydraulic fracturing) have allowed natural gas reserves previously too costly to access to become economically viable. This has in turn led to increased natural gas production in the United States (Source: http://energy.umich.edu/wp-content/uploads/fracking-in-michigan-orig-stock-2012-11-28.jpg Accessed December 9, 2013).

9.2 Appendix B

Below is one of the original well data files with blank rows removed (API number 01320442) from (Wyoming Oil and Gas Conservation Commission, N.D.). 38 of these files were collected and valid data was selected and tabulated for easier use and listed below this well record.

Well Record					
API 013 - 20442					
Operator ENCANA OIL AND GAS USA INC		Well Number 42X-11			
Lease W.H. PAUL PATENT			Lease No FEE		
Location SE NE Sec 11 T 3 N R2 E		Footage 1770 FNL and 1169 FEL			
Longitude 108.60231		Latitude 43.25349			
Elevation Gr 0	Elevation KB 5352 KB	PAVILLION			
Well ClassG		Land Type 30			
Form 2 Status FL Date 05/2013					
Total Depth 5028					
Bottom Formation FORT UNION		Formation WIND RIVER			
Unit Number					
APD Record					
---	Apd Approved 08/06/1973	Spud Date 08/06/1973	Completion Date 01/19/1974		
Casing Record					
Hole Size		Casing Size 8 5/8	Casing Depth 601		
Hole Size		Casing Size 4 1/2	Casing Depth 5027		
Completion Record					

Spud Date 08/06/1973		Completion Date 01/19/1974		Formation FORT UNION-WIND RIVER
Total Depth 5028		Plug Back 0		
IP Oil Bbls 0		IP Gas Mcf 0		IP Water Bbls 0
Reservoir Class G		Date First Production 05/31/1983		TD Formation FORT UNION
Completion Record				
Spud Date 08/06/1973		Completion Date 12/27/1973		Formation FORT UNION-WIND RIVER
Reservoir Class G				
Geological Tops				
FORT UNION	**3335**			
Cumulative Production From May 1983 To May 2013				
Oil 0 BBLS				
Gas 6,057,914 MCF				
Water 222 BBLS				
Form 2's Filed				
Production WIND RIVER				
Production FORT UNION-WIND RIVER				
Sundry Record				
Form Date	**Submission**	**Action**		
10/26/2011	SUBSEQUENT REPORT	OTHER		
8/18/2011	NOTICE OF INTENT	SOIL, GW SAMPLING		

8/11/2009	SUBSEQUEN T REPORT	REPORT RESULTS			
12/5/2006	SUBSEQUEN T REPORT	OCSRRS EVALUATION			
9/17/2005	SUBSEQUEN T REPORT	RECLAIM-SIGNED-CONDITION			
9/17/2001	SUBSEQUEN T REPORT	ADD PERFS			
1/23/1998	NOTICE OF INTENT	CHANGE DISPOSAL SITE			

The tabulation of selected well data from the 38 files obtained from WOGCC website (Wyoming Oil and Gas Conservation Commission, N.D.) is listed below:

API	Elevation (Feet)	Well Depth (Feet below surface)	Casing Depth (feet below surface)	Formation (FU = Fort Union, WR = Wind River)	Formation Top depth (feet below surface)	Reported fracturing date and depth (feet below surface)
1320442	5352	5028	601	FU	3335	(none)
1320854	5366	5103	615	WR	3140	(none)
				FU	3350	(none)
1320878	5324	5200	586	(no tops reported)	(no tops reported)	(none)
1321669	5357	6482	627	WR	3140	(none)
				FU	3300	(none)
1321691	5372	5972	598	WR	3162	(none)
				FU	3310	(none)
1321696	5358	5995	626	WR	3160	(none)
				FU	3312	(none)
1321806	5349	5540	548	WR	0	(none)
				WR BASAL	3146	(none)
				FU	3330	(none)
1321866	5337	5100	510	BASAL WR	3189	(none)
				FU	3388	(none)
				WR (BASAL SS)	3226	(none)
				FU - A	3315	(none)
				B	3567	(none)
				C	3794	(none)
				D	4034	(none)
				E	4232	(none)
				F	4504	(none)
				G	4690	(none)
				H	4946	5/1/2000 (between 5306 and 5344)

API	Elevation (Feet)	Well Depth (Feet below surface)	Casing Depth (feet below surface)	Formation (FU = Fort Union, WR = Wind River)	Formation Top depth (feet below surface)	Reported fracturing date and depth (feet below surface)
				I	5348	5/1/2000 (between 5450 and 5482)
				J	5584	(none)
				K	5786	(none)
1321968	5391	5600	626	WR	0	(none)
				FU - J	0	(none)
				FU - K	0	(none)
				FU	3300	(none)
				FU - A	3395	(none)
				FU - B	3658	(none)
				FU - C	3870	(none)
				FU - D	4048	(none)
				FU - E	4290	(none)
				FU - F	4510	(none)
				FU - G	4626	(none)
				FU - H	4886	(none)
				FU - I	5294	(none)
1322005	5377	3600	0	(no tops reported, abandoned)	(no tops reported, abandoned)	(none)
1322059	5355	5846	542	WR	3145	(none)
				FU	3286	(none)
1322060	5321	3275	327	WR	3190	(none)
1322087	5377	3600	362	WR UPPER	0	(none)
				WR BASAL	3200	(none)
				FU	3330	(none)
1322102	5357	3250	430	WR UPPER	0	(none)
				WR BASAL	3143	(none)
1322105	5334	3184	539	WR	3184	(none)
1322106	5346	3960	544	WR	3150	(none)

API	Elevation (Feet)	Well Depth (Feet below surface)	Casing Depth (feet below surface)	Formation (FU = Fort Union, WR = Wind River)	Formation Top depth (feet below surface)	Reported fracturing date and depth (feet below surface)
				FU A	3345	(none)
				FU B	3565	(none)
				FU C	3834	(none)
1322150	5353	3700	532	WR	3216	(none)
1322186	5320.9	3260	534	(no tops reported)	(no tops reported)	(none)
1322198	5369.8	3180	534	(no tops reported)	(no tops reported)	(none)
1322200	5336.1	4000	533	WR	3190	(none)
				FU A	3367	(none)
				FU B	3590	(none)
				FU C	3880	(none)
1322214	5329.3	4025	524	WR	3230	(none)
				FU A	3428	(none)
				FU B	3664	(none)
				FU C	3963	(none)
1322215	5355	3190	620	(no tops reported)	(no tops reported)	(none)
1322220	5363.4	4780	560	WR	3135	(none)
				FU	3298	(none)
1322223	5349.4	4000	574	WR	3140	(none)
				FU A	3336	(none)
				FU B	3543	(none)
				FU C	3830	(none)
1322224	5374	5850	622	WR UPPER	0	(none)
				FU	3323	(none)
1322255	5333.2	3955	635	WR	3442	(none)
				FU	3955	(none)
1322268	5378	5555	630	WR	0	1/1/2005 (between 1702 and 1706)
				FU	3318	1/1/2005 (between 4940 and 4946)

API	Elevation (Feet)	Well Depth (Feet below surface)	Casing Depth (feet below surface)	Formation (FU = Fort Union, WR = Wind River)	Formation Top depth (feet below surface)	Reported fracturing date and depth (feet below surface)
1322270	5381	6000	645	(no tops reported)	(no tops reported)	(none)
1322271	5356	4500	631	WR	0	2/1/2005 (between 2234 and 2243)
				FU	3316	2/1/2005 (between 3840 and 3844)
1322272	5362.2	3860	550	WR	0	1/1/2005 (between 1406 and 1473)
				FU	3287	1/1/2005 (between 3460 and 3466)
1322313	5347	3975	511	FU	3418	1/1/2005 (between 1713 and 1727, and between 3540 and 3548)
1322314	5354	3850	635	WR	0	(none)
				FU	0	(none)
1322324	5366	5605	621	WR	3311	(none)
				FU	5605	(none)
1322419	5379.3	4020	626	WR	3550	(none)
				FU	4020	(none)
1322586	5355	3875	642	WR	0	(none)
				FU	3243	(none)
1322601	5343	3900	643	(none listed; assumed to be WR)	0	(none)
1322624	5371	3841	640	WR	0	(none)

9.3 Appendix C

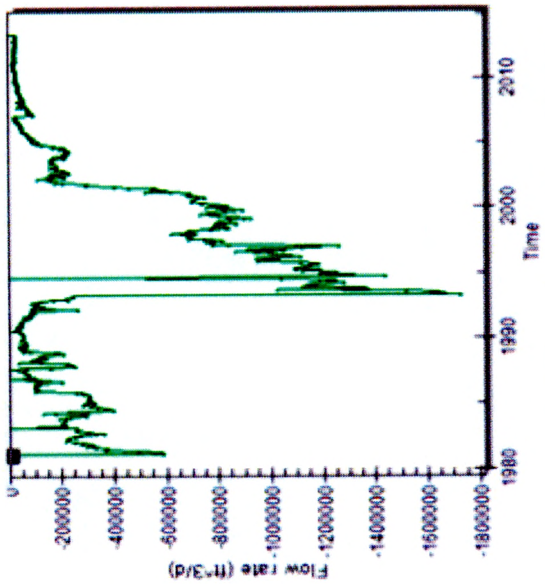

Figure C2: Production Data of Well API# 1322198

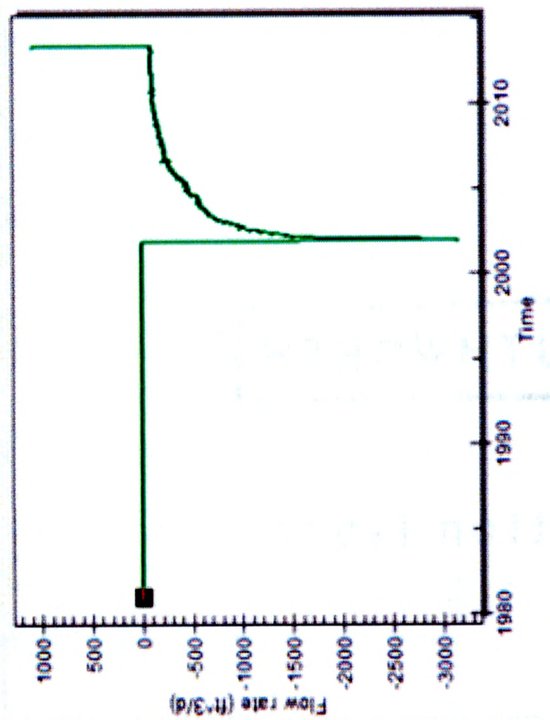

Figure C1: Production Data of Well API# 1320878

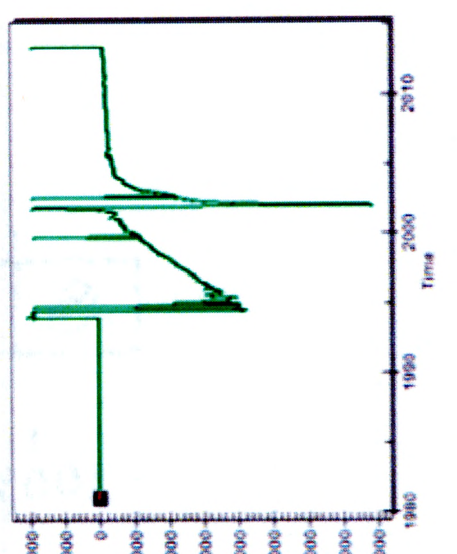

Figure C3: Production Data of Well API# 1321691

9.4 Appendix D

Compiled from (Duffield, N.D.):

Rock Type	Hydraulic Conductivity (m/sec)
Sandstone	$3x10^{-10}$ to $6x10^{-6}$
Shale	$1x10^{-13}$ to $2x10^{-9}$

Figure D1: Compiled hydraulic conductivity ranges (Duffield, N.D.)

Material	Horizontal Hydraulic Conductivity (m/sec)	Vertical Hydraulic Conductivity (m/sec)
Sandstone	$5x10^{-13}$ to 10^{-10}	$2.5x10^{-13}$ to $5x10^{-11}$
Shale	10^{-14} to 10^{-12}	10^{-15} to 10^{-13}

Figure D2: Compiled Horizontal and Vertical Hydraulic Conductivity ranges (Duffield, N.D.)

Material	S_s (ft^{-1})
Plastic clay	$7.8x10^{-4}$ to $6.2x10^{-3}$
Stiff clay	$3.9x10^{-4}$ to $7.8x10^{-4}$
Medium hard clay	$2.8x10^{-4}$ to $3.9x10^{-4}$
Loose sand	$1.5x10^{-4}$ to $3.1x10^{-4}$
Dense sand	$3.9x10^{-5}$ to $6.2x10^{-5}$
Dense sandy gravel	$1.5x10^{-5}$ to $3.1x10^{-5}$
Rock, fissured	$1x10^{-6}$ to $2.1x10^{-5}$
Rock, sound	$< 1x10^{-6}$

Figure D3: Specific storage values (Duffield, N.D.)

Calibration process (5 inches/year):

K (ft/day)	4.25E-01	1.7
Total Water In (L)	150860.09	603437.75
Total Water In (ft^3)	5327.58	21310.22
Area (m^2)	3523354.2	3523354.2
Area (ft^2)	37925032.27	37925032.27
Infow (ft^2)	18962516.14	18962516.14
Depth (ft)	0.00	0.00
Depth (in)	0.0033714380	0.0134856933
Average Recharge inches/day	0.01369863	0.01369863
Discrepancy	-0.0103271921	-0.0002129368
Estimated annual recharge for Wind River (average inches/yr)	5.00	5.00

IN:		IN:	
---		---	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	603437.7500	CONSTANT HEAD =	603437.7500
TOTAL IN =	603437.7500	TOTAL IN =	603437.7500
OUT:		OUT:	
----		----	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	603437.7500	CONSTANT HEAD =	603437.7500
TOTAL OUT =	603437.7500	TOTAL OUT =	603437.7500
IN - OUT =	0.0000	IN - OUT =	0.0000
PERCENT DISCREPANCY =	0.00	PERCENT DISCREPANCY =	0.00

Calibration Process (3 in/yr):

K (ft/day)	0.4250000000	1.0361130000
Total Water In (L)	150860.09	367782.56
Total Water In (ft^3)	5327.58	12988.13
Area (m^2)	3523354.2	3523354.2
Area (ft^2)	37925032.27	37925032.27
Infow (ft^2)	18962516.14	18962516.14
Depth (ft)	0.00	0.00
Depth (in)	0.0033714380	0.0082192452
Average Recharge inches/day	0.008219178	0.008219178
Discrepancy	-0.0048477401	0.0000000671
Estimated annual recharge for Wind River (average inches/yr)	3.00	3.00

IN:		IN:	
---		---	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	367782.5625	CONSTANT HEAD =	367782.5625
TOTAL IN =	367782.5625	TOTAL IN =	367782.5625
OUT:		OUT:	
----		----	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	367782.5312	CONSTANT HEAD =	367782.5312
TOTAL OUT =	367782.5312	TOTAL OUT =	367782.5312
IN - OUT =	3.1250E-02	IN - OUT =	3.1250E-02
PERCENT DISCREPANCY =	0.00	PERCENT DISCREPANCY =	0.00

Calibrate to 1 inch per year:

K (ft/day)	0.4250000000	0.345
Total Water In (L)	150860.09	127838.2812
Total Water In (ft^3)	5327.58	4514.57
Area (m^2)	3523354.2	3523355.2
Area (ft^2)	37925032.27	37925043.04
Infow (ft^2)	18962516.14	18962521.52
Depth (ft)	0.00	0.00
Depth (in)	0.0033714379	0.0028569432
Average Recharge inches/day	0.002739726	0.002739726
Discrepancy	0.0006317119	0.0001172172
Estimated annual recharge for Wind River (average inches/yr)	1.00	1.00

IN:		IN:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	127838.2812	CONSTANT HEAD =	127838.2812
TOTAL IN =	127838.2812	TOTAL IN =	127838.2812
OUT:		OUT:	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	127841.8125	CONSTANT HEAD =	127841.8125
TOTAL OUT =	127841.8125	TOTAL OUT =	127841.8125
IN - OUT =	-3.5312	IN - OUT =	-3.5312
PERCENT DISCREPANCY =	0.00	PERCENT DISCREPANCY =	0.00